SIMULATION AND VALIDATION OF TWO-COMPONENT FLOW
IN A VOID RECIRCULATION SYSTEM

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Oscar Eduardo Daza

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COMMITTEE MEMBERSHIP

TITLE: Simulation and Validation of Two-Component Flow
in a Void Recirculation System

AUTHOR: Oscar Eduardo Daza

DATE SUBMITTED: May 2011

COMMITTEE CHAIR: Dr. Christopher C. Pascual, Professor

COMMITTEE MEMBER: Dr. Kim A. Shollenberger, Professor

COMMITTEE MEMBER: Dr. Glen E. Thorncroft, Professor

ABSTRACT

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Oscar Eduardo Daza

Nuclear power plants rely on the Emergency Core Cooling System (ECCS) to cool down the reactor core in case of an accident. Occasionally, air is entrained into the suction piping of ECCS causing voids that decrease pumping efficiency, and consequently damage the pumps. In an attempt to minimize the amount of voids entering the suction side of the pump in ECCS, a Void Recirculation System (VRS) experiment was conducted for a proof of concept purpose. While many studies have been oriented in studying two-component flow behavior in ECCS, none of them propose a solution to minimize air entrainment. As a consequence, there are no simulation models that use computational fluid dynamics to address gas entrainment solutions in ECCS. The objectives of this thesis are to (1) simulate and investigate two-component air-water flow in a VRS that minimizes the amount of air in piping systems, using RELAP5/MOD3 as the computational tool, and (2) to validate the numerical results with respect to experimental results and observations.

A one-dimensional model of the VRS was built in RELAP5, in which eight different scenarios (replicating those from the VRS experiment) were simulated for a period of 150 seconds. Four Froude numbers of 0.8, 1.0, 1.3 and 1.6 were evaluated in two different pipe configurations, and the experimental data obtained from the VRS experiment was used to validate the numerical results obtained from these simulations. It was concluded that air recirculation occurs indefinitely throughout the entire 150 seconds of the simulation for Froude numbers up to 1.3; while for a Froude number of 1.6, air recirculation occurs for approximately 100 seconds and ceases after 125 seconds of the simulation. An average air reduction effectiveness of 90% was found for all simulation scenarios. The VRS model was successfully validated and can be used to investigate the effects of air entrainment in suction piping.

Keywords: Two-component flow, air-water, void fraction, RELAP5, CFD simulation.

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TABLE OF CONTENTS

	Page
LIST OF TABLES	ix
LIST OF FIGURES	xi
NOMENCLATURE	xv
Chapter 1. INTRODUCTION AND LITERATURE REVIEW	1
1.1. Emergency Core Cooling System	1
1.2. ECCS Gas Entrainment Solutions and Void Recirculation System.....	3
1.3. Review of existing ECCS models	5
1.4. Review of existing Two-Phase flow models.....	8
1.5. Computational Tool.....	11
1.5.1. RELAP5/MOD3 Applications	12
1.5.2. RELAP5/MOD3 Limitations	12
1.6. Objectives.....	13
Chapter 2. COMPUTATIONAL MODEL.....	14
2.1. Two-Fluid General Definitions	14
2.1.1. Froude Number	14
2.1.2. Void Fraction	15
2.1.3. Superficial Velocity	16
2.1.4. Flow Quality	16
2.1.5. Slip Ratio	17
2.2. Two-Fluid Flow Model used in RELAP5	17
2.2.1. One-Dimensional Two-Fluid Conservation Equations	18
2.2.2. Flow Regimes.....	20
2.2.3. Wall Friction Model	24

2.3.	Computational Domain	26
2.3.1.	VRS Model Geometry	26
2.3.2.	VRS Model Boundary Conditions	37
2.3.3.	VRS Model Thermal/Hydraulic settings	41
2.4.	Fluid Properties	45
2.5.	Simulation Assumptions	45
Chapter 3.	SIMULATION SCENARIOS, RESULTS AND DISCUSSION	47
3.1.	Void Recirculation Experiment.....	47
3.1.1.	Experiment Description	47
3.1.2.	Experiment Observations.....	51
3.2.	Description of Simulation Scenarios.....	64
3.3.	Convergence Test.....	65
3.3.1.	Time Independence Test	67
3.3.2.	Grid Independence Test	69
3.4.	Simulation Validation, Results and Discussion	73
3.4.1.	Mass Flow Rate Analysis.....	74
3.4.2.	Void Fraction Analysis	81
3.4.3.	Simulation and Experimental Void Fraction Validation	92
Chapter 4.	CONCLUSIONS AND RECOMMENDATIONS	96
4.1.	Conclusions	96
4.2.	Recommendations	97
	Bibliography	99
	Appendix A – VRS Piping Drawings	102
	Appendix B – VRS Pipe Data.....	104
	Appendix C – VRS RELAP5 Code	112

Appendix D – VRS Model Results	144
Appendix D.1. Mass Flow Rate Results	144
Appendix D.2. Void Fraction Results.....	148
Appendix E – VRS Simulation and Experimental Void Fraction Validation	152

LIST OF TABLES

	Page
Table 2.1. List of the main hydrodynamic building blocks used in the VRS model.....	30
Table 2.2. VRS pipe specifications and elbow resistance coefficients.....	32
Table 2.3. Enlargement and contraction loss coefficient values for various reducing bushings.	34
Table 2.4. Regular tee loss coefficient values.....	35
Table 2.5. Summary of the simulated pump flow rates as a function of the Froude number.	38
Table 2.6. Air injection scheme for various Froude numbers in the four-inch pipe, yielding a minimum initial void fraction of seven-percent.....	40
Table 2.7. Air injection scheme for various Froude numbers in the six-inch pipe, yielding a minimum initial void fraction of seven-percent.....	40
Table 2.8. Summary of the control flags used for various VRS model components.	43
Table 2.9. Summary of the controls flags used for various VRS model reducing tees.	44
Table 3.1. List of simulation scenarios for the RELAP5 VRS model.	65
Table 3.2. List of convergence tests for the RELAP5 VRS model.....	66
Table 3.3. Discretization error results based on the RE method.....	70
Table 3.4. Modified Discretization error results based on the RE method, using p $= 2.00$	73

Table 3.5. Numerical results for the average percent air removed between	
stations three and four.	85

LIST OF FIGURES

	Page
Figure 1.1. Schematic Diagram of the Emergency Core Cooling System. (Diablo Canyon Power Plant, PG&E, 2009)	1
Figure 1.2. Void migration schematic in the suction piping of the ECCS.....	3
Figure 1.3. Generic schematic of the Void Recirculation System device to be used in the ECCS.	5
Figure 2.1. Horizontal flow regimes with brief description (Chisholm D. , 1983).	21
Figure 2.2. Horizontal flow regime map used in RELAP5 (RELAP5/MOD3.2, Code Manual Volume I: Code Structure, System Models, and Solution Methods, 1995).	22
Figure 2.3. Upwards vertical flow regimes with brief description (Chisholm D. , 1983).	23
Figure 2.4. Vertical flow regime map used in RELAP5 (RELAP5/MOD3.2, Code Manual Volume I: Code Structure, System Models, and Solution Methods, 1995).	23
Figure 2.5. Isometric drawing of the VRS (Daza, Fong, Rosas, & Wong, 2009).	27
Figure 2.6. Computational schematic of the 4x4x3-inch VRS model.	28
Figure 2.7. Computational schematic of the 6x6x4” VRS model.....	29
Figure 3.1. Experimental setup of the Void Recirculation System.....	47
Figure 3.2. Lower pipe configurations used during the VRS experiment.	49
Figure 3.3. Sections of experimental interest for the Void Recirculation System.....	51

Figure 3.4. Horizontal stratified flow regime observed in the four and six-inch pipes.	52
Figure 3.5. Downward bubbly flow regime observed in the four and six-inch pipes.	54
Figure 3.6. Wavy horizontal stratified flow observed in the four and six-inch pipes.	55
Figure 3.7 Bubbly and slug flow observed in the four and six-inch pipes.	56
Figure 3.8. Slug flow observed at station three in the four and six-inch pipes.....	57
Figure 3.9. Wavy horizontal stratified and bubbly flow transition observed at station three in the four and six-inch pipes.	58
Figure 3.10. Bubbly flow observed at station four in the four and six-inch pipes.....	60
Figure 3.11. Upwards slug flow observed at the VRP for the four and six-inch pipe configurations.....	61
Figure 3.12. Upwards bubbly flow observed at the VRP for the four and six-inch pipe configurations.....	62
Figure 3.13. Taylor Bubble Train Flow Regime (Flow Regime Sample Movies).	62
Figure 3.14. Air settling before the check valve in the six-inch branch.	64
Figure 3.15. Void fraction behavior for scenario one at station three for different time steps.	67
Figure 3.16. Void fraction behavior for scenario one at station three for different mesh sizes.	69
Figure 3.17. Mass flow rate behavior for simulation scenario one: 4x4x3-inch, $Fr = 0.81$	75

Figure 3.18. Mass flow rate and void fraction behavior at the recirculation pipe, for simulation scenario one: 4x4x3-inch, $Fr = 0.81$.	76
Figure 3.19. Mass flow rate and void fraction behavior at the recirculation pipe, for simulation scenario eight: 6x6x4-inch, $Fr = 1.60$.	78
Figure 3.20. Mass flow rate behavior for simulation scenario five: 6x6x4-inch, $Fr = 0.81$.	80
Figure 3.21. Void fraction behavior for simulation scenario one: 4x4x3-inch, Fr $= 0.81$.	83
Figure 3.22. Slip ratio and void fraction behavior at stations three and four, for simulation scenario one: 4x4x3-inch, $Fr = 0.81$.	86
Figure 3.23. Void fraction behavior for simulation scenario eight: 6x6x4-inch, $Fr = 1.60$.	89
Figure 3.24. Slip ratio and void fraction behavior at pipe section after lower elbow, for simulation scenario one: 4x4x3-inch, $Fr = 0.81$.	90
Figure 3.25. Slip ratio and void fraction behavior at pipe section after lower elbow, for simulation scenario eight: 6x6x4-inch, $Fr = 1.6$.	91
Figure 3.26. Void fraction validation of the VRS model for simulation scenario one: 4x4x3-inch, $Fr = 0.81$.	93
Figure 3.27. Schematic of a pipe partially filled with water.	94
Figure A.1. 4x4x3-inch VRS Pipe Configuration Drawing.	102
Figure A.2. 6x6x4" VRS Pipe Configuration Drawing.	103
Figure D.1. Mass flow rate behavior for scenario one (4x4x3-inch, $Fr = 0.81$).	144
Figure D.2. Mass flow rate behavior for scenario two (4x4x3-inch, $Fr = 0.96$).	144

Figure D.3. Mass flow rate behavior for scenario three (4x4x3-inch, $Fr = 1.29$).	145
Figure D.4. Mass flow rate behavior for scenario four (4x4x3-inch, $Fr = 1.60$).	145
Figure D.5. Mass flow rate behavior for scenario five (6x6x4-inch, $Fr = 0.81$).	146
Figure D.6. Mass flow rate behavior for scenario six (6x6x4-inch, $Fr = 1.10$).	146
Figure D.7. Mass flow rate behavior for scenario seven (6x6x4-inch, $Fr = 1.38$).	147
Figure D.8. Mass flow rate behavior for scenario eight (6x6x4-inch, $Fr = 1.60$).	147
Figure D.9. Void fraction behavior for scenario one (4x4x3-inch, $Fr = 0.81$).	148
Figure D.10. Void fraction behavior for scenario two (4x4x3-inch, $Fr = 0.96$).	148
Figure D.11. Void fraction behavior for scenario three (4x4x3-inch, $Fr = 1.29$).	149
Figure D.12. Void fraction behavior for scenario four (4x4x3-inch, $Fr = 1.60$).	149
Figure D.13. Void fraction behavior for scenario five (6x6x4-inch, $Fr = 0.81$).	150
Figure D.14. Void fraction behavior for scenario six (6x6x4-inch, $Fr = 1.10$).	150
Figure D.15. Void fraction behavior for scenario seven (6x6x4-inch, $Fr = 1.38$).	151
Figure D.16. Void fraction behavior for scenario eight (6x6x4-inch, $Fr = 1.60$).	151
Figure E.1. Void fraction validation for scenario one (4x4x3-inch, $Fr = 0.81$).	152
Figure E.2. Void fraction validation for scenario two (4x4x3-inch, $Fr = 0.96$).	152
Figure E.3. Void fraction validation for scenario three (4x4x3-inch, $Fr = 1.29$).	153
Figure E.4. Void fraction validation for scenario four (4x4x3-inch, $Fr = 1.60$).	153
Figure E.5. Void fraction validation for scenario five (6x6x4-inch, $Fr = 0.81$).	154
Figure E.6. Void fraction validation for scenario six (6x6x4-inch, $Fr = 1.10$).	154
Figure E.7. Void fraction validation for scenario seven (6x6x4-inch, $Fr = 1.38$).	155
Figure E.8. Void fraction validation for scenario eight (6x6x4-inch, $Fr = 1.60$).	155

NOMENCLATURE

A	Pipe cross-sectional area (ft^2)
C_V	Flow Coefficient
D	Pipe Diameter (in)
Fr	Froude Number
g	Gravitational constant (ft/s^2)
j	Fluid superficial velocity (ft/s)
K	Loss coefficient
L	Pipe length (ft)
$\dot{m}$	Mass flow rate (lb/s)
P	Pressure (psi)
q	Volumetric flow rate (gpm)
Re	Reynolds number
S	Slip ratio
t	Time (s)
V	Fluid velocity (ft/s)
x	Flow quality
X	Lockhart-Martinelli parameter
Z	Volume centroid elevation (ft)

Greek Characters

α	Void fraction
θ	Volume angle, measured from horizontal (degrees)
μ	Fluid dynamic viscosity (lbf s/ft ²)
ρ	Fluid density (slug/ft ³)
v	Fluid specific volume (ft ³ /lb)
ϕ	Two-phase multiplier

Subscripts

g	Gas phase or component
i	Interface between phases
k	Phase or component (gas or liquid)
l	Liquid phase or component
m	Mixture
w	Wall

Chapter 1. INTRODUCTION AND LITERATURE REVIEW

1.1. Emergency Core Cooling System

Nuclear power plants rely on various protection systems that must be ready to operate in case of a nuclear reactor failure. One of the most important protection plans is the Emergency Core Cooling System (ECCS), which ultimately prevents a nuclear meltdown by means of transferring heat from the reactor to the borated water, which is a neutron absorber. When the ECCS is activated, borated water stored in a tank and subject to atmospheric pressure, is pumped to the nuclear reactor as shown in Figure 1.1.

Figure 1.1. Schematic Diagram of the Emergency Core Cooling System. (Diablo Canyon Power Plant, PG&E, 2009)

While this method has been used for many years and in many power plants, it has been common to see dissolved gas being transported into the ECCS piping system. An information notice from the Nuclear Regulatory Commission (NRC) was published regarding the entrainment of gas into the ECCS and containment spray systems of three main nuclear power plants (Nuclear Regulatory Commission, 2006). The source of

entrained gas in these three events was due to different conditions, but produced the same problem throughout. For example, NRC's inspection at Palo Verde Nuclear Generating Station determined that gas was being entrained because the water level fell below the suction piping. The second event described in the NRC's inspection was at the Waterford Steam Electric Station, Unit 3, where it was determined that lack of adjustments to the outside containment isolation valve led to loss of suction supply, thus leading to a medium to large Loss of Coolant Accident (LOCA), creating large gas voids within the suction piping. The last event described in this inspection was at the Clinton Power Station, where it was determined that an inappropriate method was used to calculate vortexing at the pump's intake. Another reason for the entrainment of gas into ECCS piping systems, which is not discussed in this information notice from the NRC and was specifically reported at the Diablo Canyon Power Plant (Avila Beach, CA), is a consequence of the depressurization of the gas in the water tank. Gas depressurization occurs when the local pressure falls below the saturation pressure of the gas. When this happens, a water-gas flow is generated and later transported into the piping system creating gas voids as specifically shown in Figure 1.2. Large voids in the suction side of the pump can create cavitation, thus decreasing pump efficiency, lifetime, while adding to the maintenance and repair costs. Even though some gas voids can be vented using relief valves, other gas voids exist near the nuclear reactor where these types of valves cannot be installed for safety purposes. For this reason, a series of solutions have been proposed in the nuclear industry to minimize or eliminate the gas voids present in the ECCS piping system. These solutions are discussed in the next section and are intended to inform the reader about possible and existing solutions.

Figure 1.2. Void migration schematic in the suction piping of the ECCS.

1.2. ECCS Gas Entrainment Solutions and Void Recirculation System

Possible solutions proposed by the NRC in a Generic Safety Issue Report (Nuclear Regulatory Commission, 2010) to minimize or prevent damage due to entrained gas into ECC systems are as follows:

- a) Install gas sensors in the suction piping to prevent pump startup or valve opening. Emergency operations are to be resumed once single-phase flow (i.e. water flow) has been fully established in the pipes.
- b) Control the sequencing of the pumps during ECCS startup.
- c) Align one of the suction pipes to the condensate storage tank.
- d) Install anti-vortexing devices to suction strainers in the location of the water source.

While these ideas still need to be carefully thought due to their practicality and cost effectiveness, other power plants need to mitigate the problem immediately. Recently, Westinghouse Electric Company LLC published a report on the investigation of a

simplified equation for gas transport in ECCS (Westinghouse Electric Company LLC, 2011). The simplified equation (SE) helps to find the maximum amount of gas volume in pump suction piping, as a function of gas volume high points, system pressures and flows. Even though the SE is based on a variety of assumptions and is limited to specific pump suction piping configurations and flow regimes, it allows the ECCS to be activated safely without risking pump damage. In fact, the Diablo Canyon Power Plant (DCPP) has been one of the first plants to successfully use this SE, and is currently updating safety procedures to keep the ECCS under normal operating conditions. In addition of using the SE, DCPP has also been proactive at minimizing the amount of gas entrained by installing a “void header” that traps the air in a collector tank. Unfortunately, this tank needs to be vented periodically by an operator, thus adding to the cost of labor and time.

With the intention of solving this problem without the need of frequent human interaction, California Polytechnic State University (San Luis Obispo, CA) partnered with DCPP to develop a self-contained system. This device, called a “Void Recirculation System” (VRS), consists of a vertical pipe connecting the lower and upper main suction piping allowing gas recirculation with the use of a check valve to prevent water back flow (Daza, Fong, Rosas, & Wong, 2009). Figure 1.3 describes a generic schematic for the VRS device, where gas voids migrate from the water tank and through the upper suction piping, then transported down through a 90 degree elbow, a vertical downcomer, another 90 degree elbow and a lower horizontal suction pipe. The void recirculation pipe is to be placed before the pump, where gas recirculates upwards and around the main suction piping as depicted in the green arrows.

Figure 1.3. Generic schematic of the Void Recirculation System device to be used in the ECCS.

This device was tested under different flow rates, initial void quantities, and bottom pipe configurations. Air was injected in the system by using an air compressor and the VRS was tested on the discharge side of the pump, rather than on the suction side, for the sake of the experiment. Void fraction measurements were taken at stations one (before the upper tee), two (after the upper tee), three (before the lower tee) and four (after the lower tee). The objective of this experiment was to verify the design of the VRS and to select the best bottom piping configuration for each of the tested scenarios. The data recorded from this experiment will be used in this thesis to validate the VRS concept using a thermal-hydraulic computer code called RELAP5/Mod3.

1.3. Review of existing ECCS models

There are several investigators who have modeled a variety of scenarios in ECCS and have contributed to the analysis and prediction of LOCAs. The main objective in

these contributions is to provide better management and operating procedures in case of nuclear accidents. Sarrette and Bestion, for example, investigated the potential release of nitrogen gas dissolved in water during depressurization in the accumulator of the ECCS at the Loviisa Nuclear Power Plant (Sarrette & Bestion, 2003). The first part of their work consisted of performing a series of degassing tests in order to find the time constant associated with the nitrogen gas release in a vertical pipe. Then, a non-condensable gas dissolution-release model was created using CATHARE (Code Avancé de Thermohydraulique pour Accidents de Réacteur à Eau), a thermal-hydraulic code for the nuclear safety analysis of Pressurized Water Reactors (PWR). An interfacial friction model consistent with the flow configuration seen in the experimental results, along with the gas-release time constant previously found, was later implemented in CATHARE. Finally, the code was used to investigate the effects of nitrogen degassing for LOCA scenarios. Numerical results showed better agreement with experimental results for the case of delayed degassing than for faster degassing.

A similar work at DCP, where the effect of nitrogen gas entrained was studied in ECCS piping systems, was the effort done by Phillips in his water hammer simulation using RELAP5 (Phillips, 2003). During the pump startup operation, pressure waves can be generated if gas voids are present in the piping system. This effect, commonly known as a water hammer, can create high pipe stresses in elbows due to rapid change in direction, thus leading to pipe damage and possible ECCS failure. Pipe stresses modeled in RELAP5, measured as hydraulic forces, were subject to 100% and 50% void models in order to fully analyze the water hammer effect. Even though the model provided a

reasonable prediction of hydraulic forces, the maximum calculated values continue to be under the safety order of magnitude during a LOCA.

Other investigators have focused their research in different LOCA scenarios in order to develop severe accident management guidelines, and to provide better insight on the ECCS fluid transport model. For instance, a RELAP5 model was developed to analyze the steam-zirconium oxidation and pipe rupture in the ECCS at the Ignalina Nuclear Power Plant (Kaliatka & Uspuras, 2008). Zirconium is used as a cladding material for nuclear rods due to its low thermal absorbance and high corrosion resistance. However, steam can oxidize the zirconium cladding at high temperatures (approximately at 1200°C) by producing an exothermic reaction (release of heat), accompanied by the release of hydrogen gas. If this oxidation is not controlled, pipe rupture can occur. The code results were first validated against existing data in the RBMK (for Russian *reaktor bolshoy moshchnosti kanalniy*) type reactors at the Leningrad Nuclear Power Plant and later used at the Ignalina plant for the development of accident management guidelines. The results obtained in RELAP5 were determined to be acceptable for plant operating procedures. In another investigation, Groudev and Gencheva studied the advantages and disadvantages of main loop isolating valves in case of a steam generator tube rupture (Groudev & Gencheva, 2004). The thermal-hydraulic results, modeled in RELAP5, showed that the use of main isolation valves is achievable, and the operator can bring the plant to safe running conditions.

It is important to note that few investigators, such as Sarrette, Bestion and Phillips, have actually dealt with gas entrainment models. However, during the literature research, no publication was found that discussed neither the implementation of gas

entrainment solutions nor the modeling of possible solutions in ECCS piping systems. For this reason, the motivation of using RELAP5/MOD3 to build a computational model, representing the experimental setup of the VRS, was initiated to simulate gas entrainment solutions in ECCS. The numerical results obtained were used to evaluate the practicality of one of the first gas entrainment solutions, and were validated against the results obtained from the VRS experiment. This one involves the subject of two-phase flow in pipes, for which a literature review of these models will be discussed in the next section.

1.4. Review of existing Two-Phase flow models

Since the VRS experiment mainly focused on the void fraction behavior at the upper and lower main pipes, and not the effects that elbows had on the recirculation path, the following literature research also focuses on two-phase horizontal flows and flow separation at tee junctions. Moreover, the research will be limited to horizontal stratified flows since this was the flow regime that was observed during the VRS experiments.

The investigation and analysis of two-phase flows has been carried out by numerous researchers depending upon the conditions of interest. The contributions done by Ishii and Mishima have been of great value to the multi-phase community because they have formalized all equations to be used for mass, momentum and energy conservation (Ishii, 1975; Ishii & Mishima, 1984). Other researchers such as Taitel, Dukler and Chisholm have also contributed to this immense field by providing theoretical approaches to the prediction of pressure drop in pipelines (Taitel & Dukler, 1976; Chisholm, 1968).

With the introduction of today's powerful computational techniques, it has been possible to better predict many variables of interest for two-phase flow (e.g. void fraction, pressure drop, flow regimes, etc.). For instance, Newton and Behnia (2001) developed a numerical model for horizontal stratified wavy gas-liquid pipe flow, that predicted liquid holdup, pressure drop, wall and interfacial shear stresses. The main objective of this numerical model was to gain independence of empirical closure relations, by providing a bipolar coordinate system, along with a $\kappa - \epsilon$ turbulence model at low Reynolds numbers, allowing the solution of the governing equations for each phase without inputting empirical wall functions. The proposed numerical model was then compared to existing mechanistic models, and the prediction of the measured values were in acceptable agreement with the experimental data. In a similar investigation, a model was proposed using the Reynolds-averaged Navier-Stokes (RANS) equations, with the $\kappa - \omega$ turbulence model for fully developed horizontal stratified flow in pipes (de Sampaio, Faccini, & Su, 2008). This model used a finite element mesh, bipolar coordinates, the Newton-Raphson root finding scheme, and focused on simulating the wall and interfacial shear stresses to provide better insight on the interaction of gas-liquid flows, with the objective of validating the use of the $\kappa - \omega$ turbulence model. The predicted values were then compared to experimental data, showing that the turbulence model was suitable for horizontal stratified flows. Yet another numerical simulation was carried out using FLUENT to determine the interfacial friction factor for horizontal stratified gas-liquid 3D flows (Sidi-Ali & Gatignol, 2010). Velocity profiles, wall-gas shear stresses and interfacial shear stresses numerical results were compared to seven different experiments and one numerical model. The results comparison showed to be in excellent agreement

for velocity profiles, and acceptable agreement for wall-gas and interfacial shear stresses, confirming the validity of the turbulence model used.

Simulation of the bottom horizontal tee for the VRS experiment can be seen as a form of two-phase separator, with the exception that the gas recirculation path is actually connected to the same main pipe loop. The orientation of the tee, where there is a horizontal run and a vertical branch (with upwards flow), is of particular interest for the validation of the VRS device and hence the computational model presented in this thesis. In the attempt of analyzing this specific type of flow configuration, Margaris (2007) proposed a mathematical algorithm to model the separation of gas-liquid two-phase flow at a tee junction. The experimental and numerical models both assumed a horizontal straight pipe before the tee junction with slug flow at the tee inlet, the air was separated through the vertical branch and the water continued its path through the horizontal run. The vertical branch then connected to a horizontal settling pipe, where further separation was allowed. The air continued its path into an independent gas line, and the water fell downwards into the lower main horizontal pipeline through a vertical pipe. Air and water mass flow rates were compared, as well as void fraction and pressure drop at the tee junction and at the settling pipe. The numerical results obtained showed satisfactory results with respect to the experimental data, and the mathematical algorithm was successfully validated. Margaris also suggested the implementation of this algorithm into other computer codes due to its easy incorporation of one-dimensional multiphase flow. Other similar investigations carried out by Ottens et al. (2001) and Baker et al. (2008), studied the transient effects in gas-liquid separators by using different pipe configurations and tee orientations. Nonetheless, the experiments carried out in both works showed that

the different phases were completely separated in different pipelines, as was the case for the research done by Margaritis.

1.5. Computational Tool

Numerical simulations for nuclear power plant systems can be done in a variety of computational fluid dynamic (CFD) solvers depending upon the specific problem to be analyzed. Software such as FLUENT (by ANSYS), SolidWorks Flow Simulation and Flow-3D could potentially be used to solve two-phase flow simulation problems. The software selection mainly depends on the computational domain to be solved, being either a small subsystem (e.g. flow around an object), or the analysis of a complete system (e.g. power plant thermal and hydraulic systems). Since this thesis analyzes air-water flow in nuclear power plant pipelines that change both in diameter and orientation, then the current study will use RELAP5/MOD3 to simulate the VRS device.

RELAP5 stands for Reactor Excursion and Leak Analysis Program, and is the fifth version of all RELAP codes. It is a thermal/hydraulic computer code developed for the U.S. NRC for the use of rulemaking, operating guidelines and as nuclear plant analyzer. Hence, it is the only code accepted by the NRC if simulation data is to be presented in any form of publication. In addition, DCP uses this code to analyze the plant, and the code developed in this study can potentially be used at their site for further development. RELAP5 computer code is written in FORTRAN 77 and uses one-dimensional two-fluid conservation equations that are formulated in terms of volume and

time-averaged parameters. The code also uses a semi-implicit finite-difference technique to solve the computational domain and is first-order accurate in space and time.

1.5.1. RELAP5/MOD3 Applications

The computer code RELAP, being in its fifth version, has a variety of co-current and new models that are used to simulate and analyze specific nuclear plant systems such as steady-state and transient problems, Emergency Core Cooling mixing component model, Zirconium-water reaction model, correlations for interfacial friction in all geometries, an improved cross flow model and many more (RELAP5/MOD3.2, Code Manual Volume I: Code Structure, System Models, and Solution Methods, 1995). In general, RELAP5 is commonly used to simulate LOCA's, loss of feed-water, station blackout and turbine trip. It can also be used to simulate mixtures of steam, water, and non-condensable gases.

1.5.2. RELAP5/MOD3 Limitations

As previously mentioned, it is wise to carefully choose the CFD tool to be used for each problem since not all software is capable of analyzing an entire scope of computational domains. In the case of RELAP5, the code has two main limitations that were depicted during the learning phase of the program. First, the code cannot be used to analyze flows around objects. For example, the analysis of variables such as pressure and temperature gradients, streamlines, and velocities cannot be done on the problem of flow through an orifice. Second, the process of nodalization is limited to the L/D ratio (L is

the volume length and D is the volume diameter) for numerical stability. There are other limitations depending upon the models to be used within the program, and is strongly suggested to review the components to be used, along with their limitations, before deciding to use RELAP5.

1.6. Objectives

The objectives of this thesis are to (1) simulate and investigate two-component air-water flow in a void recirculation system that minimizes the amount of air in piping systems, using RELAP5/MOD3 as the computational tool, and (2) to validate the numerical results obtained from the void recirculation system model with respect to experimental results and observations.

The objectives previously mentioned will be approached in Chapter 2, where the computational model is explained from both the theoretical and geometrical viewpoints; and in Chapter 3, where the results from the model are discussed and validated against experimental results. Chapter 4 highlights the most significant achievements of this work and provides recommendations for future work.

Chapter 2. COMPUTATIONAL MODEL

2.1. Two-Fluid General Definitions

The two-fluid flow model used in RELAP5, which will be discussed in the next section, requires the definition of unique parameters that are pertinent to this field of study. It is important to note that there are several parameters used in two-fluid flow, but only the concepts of interest will be defined.

2.1.1. Froude Number

The Froude number is a dimensionless parameter representing the ratio of inertia to gravitational forces. In general, it can be applied to open-channel flow (Jain, 2001), where the free surface of the water is subject to atmospheric pressure; and in pipe flow, where gaseous and liquid phases interact with each other (i.e. two-fluid flow). The Froude number equation is as follows:

$$Fr = \frac{V_l}{\sqrt{\frac{(\rho_l - \rho_g)}{\rho_l} g D}} \quad (2.1)$$

where V_l represents the liquid velocity, ρ_l the liquid density, ρ_g the gas density, g the gravitational constant and D the inside pipe diameter. Because $\rho_l \gg \rho_g$, for the case of water and air as the main working fluids, then:

$$Fr \cong \frac{V_l}{\sqrt{g D}} \quad (2.2)$$

The Froude number categorizes the flow in three main regimes: $Fr < 1$ for subcritical flow, $Fr = 1$ for critical flow and $Fr > 1$ for supercritical flow (Fox, McDonald, & Pritchard, 2006). Previous works, for example, analyzed the influence of the Froude number in determining the frequency at which air-water horizontal slug flow occurs (Woods & Hanratty, 1999). In this analysis, it was determined that Froude numbers less than unity led to gravity waves upstream, caused by the formation of slug flows. In a similar example, the Froude number was used to characterize and predict the transition from horizontal stratified to slug flow (Kadri, Mudde, Oliemans, Bonizzi, & Andreussi, 2009). Because of the Froude number significance in the industry, this paper will use the parameter in discussion for flow regime predictions and void fraction calculations.

Other basic parameters used in two-fluid flow are void fraction, superficial velocity, slip ratio and flow quality (Ghiaasiaan, 2008). These will be discussed in more detail in the following sections, will be used in different models and correlations, and assume the form of composite-averaged parameters.

2.1.2. Void Fraction

The void fraction can be defined as the ratio of the area occupied by the gas to the total cross-sectional area as follows:

$$\alpha = \frac{A_g}{A} \quad (2.3)$$

where A_g is the area occupied by the gas and A is the total cross-sectional area of the pipe.

2.1.3. Superficial Velocity

The superficial velocity of each fluid is defined as the mean velocity if only that fluid flowed in the pipe, thus,

$$j_l = \frac{q_l}{A} \quad (2.4)$$

$$j_g = \frac{q_g}{A} \quad (2.5)$$

where q_l and q_g are the liquid and gas flow rates, respectively.

The mixture center-of-volume velocity is the sum of both superficial fluid velocities, then

$$j = j_l + j_g \quad (2.6)$$

In the same way, the superficial fluid velocities are related to their fluid intrinsic velocities as follows:

$$j_l = (1 - \alpha)V_l \quad (2.7)$$

$$j_g = \alpha V_g \quad (2.8)$$

The superficial velocities are used to generalize flow regime maps and calculate void fraction values.

2.1.4. Flow Quality

The flow quality is the ratio of the gas to mixture mass flow rates as follows:

$$x = \frac{\dot{m}_g}{\dot{m}_g + \dot{m}_l} \quad (2.9)$$

where $\dot{m}_g$ and $\dot{m}_l$ represent the gas and liquid mass flow rates, respectively. This parameter will also be used to calculate both void fraction and two-fluid pressure drop values.

2.1.5. Slip Ratio

The slip ratio is a relationship between the gas and liquid velocities that allows describing velocity differences between the phases or components as follows:

$$S = \frac{V_g}{V_l} \quad (2.10)$$

The slip ratio has a direct and indirect proportional relationship with the gas and liquid velocities, respectively. More specifically, as the gas velocity decreases, the slip ratio decreases as well, implying that the gaseous phase or component moves slower than the liquid component. This parameter will be used to validate numerical results.

2.2. Two-Fluid Flow Model used in RELAP5

Two-fluid flow is concerned with the simultaneous flow of two fluids in a given space. It can occur in many industrial applications such as boiling and pressurized water reactors, evaporators, condensers, jet pumps and many more. This concept can be divided into two subcategories for which they are well known in the industry (Wallis, 1969):

1. *Two-Phase flow*, in which the fluids can be of the same component but of different states of matter, such as gas, liquid or solid.
2. *Two-Component flow*, in which the fluids do not consist of the same chemical substance, such as water and air.

These three terms will be used interchangeably throughout this paper depending on the matters to be discussed, but all mathematical notions and derivations are identical. Another term used in different references, and which will not be discussed in this paper, is *Multi-Phase flow*, which concerns the simultaneous flow of more than two phases or components.

2.2.1. One-Dimensional Two-Fluid Conservation Equations

Two-fluid flows follow the same laws as those described in fluid dynamics, and in fact are derived from single-phase or single-fluid conservation equations, though they are more complex and numerous since more variables have to be accounted for. The basic field one-dimensional equations for the two-fluid model consists of two continuity equations, two momentum equations and two energy equations as follows (RELAP5/MOD3.2, Code Manual Volume I: Code Structure, System Models, and Solution Methods, 1995):

Continuity Equation:

$$\frac{\partial}{\partial t}(\alpha_k \rho_k) + \frac{1}{A} \frac{\partial}{\partial x}(\alpha_k \rho_k V_k A) = \Gamma_k \quad (2.11)$$

where the subscript k denotes the phase or component of interest, that is $k = g$ for the gas phase and $k = l$ for the liquid phase; and Γ is the gas or liquid generation depending on the phase of interest.

Momentum Equation:

$$\begin{aligned}
 \alpha_k \rho_k A \frac{\partial V_k}{\partial t} + \frac{1}{2} \alpha_k \rho_k A \frac{\partial V_k^2}{\partial x} \\
 = -\alpha_k A \frac{\partial P}{\partial x} + \alpha_k \rho_k B_x A - (\alpha_k \rho_k A) F W_k (V_k) + \Gamma_k A (V_{ki} - V_k) \\
 - (\alpha_k \rho_k A) F I_k (V_k - V_j) \\
 - C \alpha_k \alpha_j \rho_m A \left[\frac{\partial (V_k - V_j)}{\partial t} + V_j \frac{\partial V_k}{\partial x} - V_k \frac{\partial V_j}{\partial x} \right]
 \end{aligned} \tag{2.12}$$

where the subscript i is the interface between the phases, j is the opposite phase of interest, and m represents the flow mixture. Also,

P = Pressure

B = Body force (i.e. gravity and pump head)

FW = Wall frictional drag coefficient

FI = Interface frictional drag coefficient

C = Virtual mass coefficient

Energy Equation:

$$\begin{aligned}
 \frac{\partial}{\partial t}(\alpha_k \rho_k U_k) + \frac{1}{A} \frac{\partial}{\partial x}(\alpha_k \rho_k U_k V_k A) \\
 = -P \frac{\partial \alpha_k}{\partial t} - \frac{P}{A} \frac{\partial}{\partial x}(\alpha_k V_k A) + Q_{wk} + Q_{ik} + \Gamma_{ik} h_k^* + \Gamma_w h'_k \\
 + DISS_k
 \end{aligned} \tag{2.13}$$

where,

U = Specific internal energy

Q_{wk} = Phasic wall heat transfer

Q_{ik} = Interfacial heat transfer

h_k^* = Phasic enthalpy associated with bulk interface mass transfer

h'_k = Phasic enthalpy associated with wall interface mass transfer

$DISS$ = Phasic energy dissipation (sums of wall friction and pump effects)

2.2.2. Flow Regimes

Two-phase flow patterns or regimes can occur in many ways depending upon volume orientation, diameter, flow rates, fluid density, fluid viscosity, surface tension, and other parameters. The main flow regimes seen in horizontal flow are bubbly, plug, stratified, stratified-wavy, slug and annular flow (Chisholm, 1983). Figure 2.1 briefly describes the most common horizontal flow regimes seen in two-phase flow. The regimes are organized in ascending gas flow rates such that bubbly flow has the lowest gas flow rate, and annular flow has the highest gas flow rate. In order to determine the type of flow regime, RELAP5 uses a specific horizontal flow regime map that is based on several empirical correlations, and only applies to volume orientations between 0° and

45°. Figure 2.2 shows the horizontal flow regime map used in RELAP5, consisting of horizontally stratified, bubbly, slug, annular mist, and mist-pre-CHF (critical heat flux) regimes. The shaded regions seen in the figure are the flow regime transition areas that also follow a set of criteria and are a function of void fraction limits, mass flux ranges, superficial velocities and fluid properties.

Figure 2.1. Horizontal flow regimes with brief description (Chisholm, 1983).

Figure 2.2. Horizontal flow regime map used in RELAP5 (RELAP5/MOD3.2, Code Manual Volume I: Code Structure, System Models, and Solution Methods, 1995).

Similarly, a variety of two-phase flow regimes can be found in vertically oriented channels. The most common vertical flow regimes are bubbly, churn, slug and annular (Chisholm, 1983). These regimes are depicted in Figure 2.3, followed by a brief description for each flow regime. Downwards vertical flows share the same flow regimes as upwards flows. As was the case for the horizontal flow regime map, RELAP5 also uses a specific vertical flow regime map that only applies to volume orientations between 45° and 90° , and are also based on several empirical correlations. Figure 2.4 describes the vertical flow regime map used in RELAP5, consisting of vertically stratified, bubbly, slug, annular mist, inverted annular, inverted slug and mist regimes. The shaded regions in the figure are the flow regime transition areas and are subject to a similar set of criteria, as previously described in the horizontal flow regime section.

Figure 2.3. Upwards vertical flow regimes with brief description (Chisholm, 1983).

Figure 2.4. Vertical flow regime map used in RELAP5 (RELAP5/MOD3.2, Code Manual Volume I: Code Structure, System Models, and Solution Methods, 1995).

2.2.3. Wall Friction Model

The wall friction calculated in RELAP5 is based on the flow regime maps previously discussed, in that each flow regime provides a criterion to determine the wall friction for each phase. It is essential to note that only wall shear effects are included, losses due to enlargement and contraction devices are calculated using mechanistic models, and losses due to elbows are modeled using flow loss coefficients that must be input by the code user.

The wall friction model is based on the two-phase multiplier approach, where the Heat Transfer and Fluid Flow Service (HTFS)-modified Baroczy correlation (RELAP5/MOD3.2, Code Manual Volume I: Code Structure, System Models, and Solution Methods, 1995) is used to find the two-phase multiplier. The total friction pressure drop in terms of the pure phasic wall friction pressure drop is

$$\left(\frac{dP}{dx}\right)_{2\phi} = \phi_k^2 \left(\frac{dP}{dx}\right)_k \quad (2.14)$$

where ϕ_k is the pure phase (fluid or gas) two-phase multiplier, and 2ϕ is short for two-phase. The phasic wall friction pressure gradient is as follows:

$$\left(\frac{dP}{dx}\right)_k = \frac{\lambda'_k (Re'_k) \dot{m}_k}{2D\rho_k A^2} \quad (2.15)$$

where λ is the single-phase friction factor, the prime denotes the pure liquid or pure gas condition, and Re'_k is the Reynolds number defined as

$$Re'_k = \frac{\dot{m}_k D}{\mu_k A} \quad (2.16)$$

where μ_k is the dynamic viscosity. The mass flow rate as a function of phasic void fraction, density, velocity and area can be expressed as

$$\dot{m}_k = \alpha_k \rho_k V_k A Re'_k = \frac{\dot{m}_k D}{\mu_k A} \quad (2.17)$$

Finally, the Lockhart-Martinelli parameter can be defined as the ratio of the pure two-phase multipliers, and are related to their pure phasic wall pressure drop as follows:

$$X^2 = \frac{\left(\frac{dP}{dx}\right)_l}{\left(\frac{dP}{dx}\right)_g} = \frac{\phi_g^2}{\phi_l^2} \quad (2.18)$$

The respective pure liquid and gas two-phase multipliers can be found by using the HTFS-modified Baroczy correlation:

$$\phi_l^2 = 1 + \frac{C}{X} + \frac{1}{X^2} \quad (2.19)$$

$$\phi_g^2 = X^2 + CX + 1 \quad (2.20)$$

where C is the correlation coefficient and is a function of the scalar mass flux and other dimensionless parameters (RELAP5/MOD3.2, Code Manual Volume I: Code Structure, System Models, and Solution Methods, 1995).

2.3. Computational Domain

2.3.1. VRS Model Geometry

The computational domain analyzed in this study was based on the experimental fixture of the VRS, which can be fully appreciated in Figure 2.5. The test fixture consisted of a 1000 gallon tank, a six-inch trash pump and three main pipe subassemblies: four-inch, six-inch and eight-inch. Due to the limited air injection power available to the project, the eight-inch pipe was not able to be tested with the initial amount of void fraction requested by DCPD. For this reason, only the four and six-inch pipe subassemblies were able to be tested, which are consequently the experimental scenarios to be modeled in RELAP5. The flow path starts at the tank, where the pump is drawing water through the six-inch suction pipe and later discharged to the main six-inch pipe. The flow path is then directed upwards where it is divided into three main pipe subassemblies or branches. Only one main branch is allowed to operate during the experiment by opening the ball valve that corresponds to the branch of interest. The flow path then continues through the main branch until it encounters the main return line, which ultimately leads to the same tank. Air was injected with a two-horsepower, 33 gallon, 150 maximum psi compressor, at locations before the upper tee.

Figure 2.5. Isometric drawing of the VRS (Daza, Fong, Rosas, & Wong, 2009).

The test fixture configuration was then coded into RELAP5 with the same physical hydrodynamic characteristics, such as pipe lengths, pipe roughness, fittings, loss coefficients, etc. Because there were several bottom tee configurations tested during the experiment, this study will only focus on the pipe configurations that yielded more air removal from the system. In particular, the bottom tees 4x4x3-inch and 6x6x4-inch configurations will be analyzed in the code. Figure 2.6 and Figure 2.7 show the computational schematic representation of the VRS that was used to build the code in RELAP5. The component number selection was based on the flow path direction, and all pipe data was condensed under a single spreadsheet, as seen in Appendix B – VRS Pipe Data.

Figure 2.6. Computational schematic of the 4x4x3-inch VRS model.

Figure 2.7. Computational schematic of the 6x6x4 VRS model.

A list of the experimental hydrodynamic components along with the chosen hydrodynamic building blocks to be modeled in RELAP5 can be seen in Table 2.1. A label and brief description of the building block function accompanies the hydrodynamic components for clarity. The VRS code built in RELAP5 can be seen in Appendix C – VRS RELAP5 Code.

Table 2.1. List of the main hydrodynamic building blocks used in the VRS model.

Hydrodynamic Experiment Component	Hydrodynamic Building block	Label	Function
Tank	Time-dependent volume	TMDPVOL	Simulates a reservoir with constant water level.
Pipe	Pipe	PIPE	Simulates a pipe in the system.
Pump	Time-dependent junction	TMDPJUN	Connects two blocks and specifies boundary conditions.
Tee	Branch	BRANCH	Connects three or more blocks in a system.
Check Valve	Valve	VALVE	Connects two blocks and simulates a valve action.
Ball Valve	Valve	VALVE	Connects two blocks and simulates a valve action.
-	Single junction	SNGLJUN	Connects two blocks.

2.3.1.1. VRS Tank/Pump Model

As described in Table 2.1, the water tank (component 200 from Figure 2.6) was modeled as a TMDPVOL to represent a water reservoir with constant water level (or constant pressure), and temperature. The pump was modeled using a combination of both the TMDPVOL and TMDPJUN (component 205) in order to set the boundary conditions for the VRS model. The pump model boundary conditions are a function of time, pressure, temperature and mass flow rate.

2.3.1.2. VRS Pipe Model

All pipe components and fittings, such as elbows, tees and bushing reducers, were modeled using the PIPE component in RELAP5. Appendix B summarizes the entire pipe data used in the code, consisting of the following main parameters: component name, subcomponent name, pipe length, pipe diameter, length/diameter ratio, flow area, resistance coefficient, volume angle, quality, volume centroid elevation and volume centroid pressure.

All piping information was obtained from the senior project experiment report (Daza, Fong, Rosas, & Wong, 2009), following the piping diagrams and computational schematics as references. The length/diameter ratio, which has to be greater than unity for numerical stability, is the relationship between the sub volume length to total pipe diameter.

Pipe diameters, flow area and elbow resistance coefficients were obtained by using the pipe specifications in Table 2.2. The elbow loss coefficient (K) was obtained by performing the following calculation (Crane Corporation, 1988):

$$K = 30f_T \quad (2.21)$$

where f_T is the pipe friction factor, and 30 is the coefficient for an elbow.

Table 2.2. VRS pipe specifications and elbow resistance coefficients.

Nominal pipe size (in)	Mean outside diameter (in)	Minimum Wall thickness (in)	Inner Diameter (in)	Flow Area (ft ²)	Pipe Friction Factor f_T	90° Elbow K
2	2.375	0.154	2.067	0.0233	0.019	0.570
3	3.500	0.216	3.068	0.0513	0.018	0.540
4	4.500	0.237	4.026	0.0884	0.017	0.510
6	6.625	0.280	6.065	0.2006	0.015	0.450
8	8.625	0.322	7.981	0.3474	0.014	0.420

Even though the K values for a 90° elbow were used throughout the code, it is important to note that the two elbows associated with pipe components 320 and 420 were modeled as 45° elbows, by keeping the former elbow loss. This was done after a simulation sensitivity analysis, where the measurements of interest were in better agreement with respect to the experimental results. In addition, it allows the code to calculate all conservation equations with a smoother transition between horizontal and vertical planes.

The volume angles, varying from 90° to -90°, represent the pipe orientation for flow direction specification. The quality is a ratio of the non-condensable mass to the system's total mass, similar to the concept of flow quality previously explained. This

value was defined as zero throughout all piping networks since there was no initial air in the system. Instead, air was injected into the pipes at steady-state conditions.

The volume centroid elevation and pressure were calculated using the following expressions:

$$Z_i = Z_{i-1} + 0.5L_i \sin\theta_i + 0.5L_{i-1} \sin\theta_{i-1} + 0.5 \frac{D_{i+1}}{12} \cos\theta_{i+1} + 0.5 \frac{D_{i-1}}{12} \cos\theta_{i-1} \quad (2.22)$$

$$P_i = P_{i-1} + \left[\frac{(Z_{i-1} - Z_i)}{(1 - \alpha v_g)} + \alpha_l v_l \right] / 144 \quad (2.23)$$

where

Z_i = elevation of the i th volume centroid (ft)

L_i = length of the i th volume (ft)

θ_i = angle of the i th volume measured from horizontal (degrees)

D_i = diameter of the i th volume (in)

P_i = pressure of the i th volume (psi)

v_k = phasic specific volume of the i th volume (ft³/lb)

The volume centroid elevation and pressure will remain the same if the volume angle is zero.

Enlargements and contractions (reducing bushings) were modeled by inputting the forward and reverse loss coefficients into the PIPE model. Forward and reverse loss coefficients are used for co-current and counter-current flows, respectively. The loss

coefficient (K) for enlargements and contractions, were calculated by using the following expressions (Crane Corporation, 1988):

$$K = \frac{(1 - \beta^2)^2}{\beta^4} - \text{enlargement} \quad (2.24)$$

$$K = \frac{0.5 \sqrt{\sin \frac{\omega}{2}} (1 - \beta^2)}{\beta^4} - \text{contraction} \quad (2.25)$$

where β is the ratio of diameters of the small (D_1) to large (D_2) pipes, and ω is the angle of divergence measured in radians. The divergence angle must satisfy the condition $45^\circ < \omega \leq 180^\circ$ and was calculated as:

$$\omega = \tan^{-1} \left(\frac{D_2 - D_1}{N} \right) \quad (2.26)$$

Where N is the socket to socket bottom dimension (Spears Manufacturing Company, 2010). Table 2.3 summarizes all loss coefficient values for several enlargement and contraction devices used in the VRS model.

Table 2.3. Enlargement and contraction loss coefficient values for various reducing bushings.

Large diameter D_2 (in)	Small diameter D_1 (in)	Reducing Bushing	Dimension N (in)	ω (rad)	Enlargement K	Contraction K
3	2	3x2	0.563	1.058	0.309	0.999
4	2	4x2	1.031	1.095	0.563	4.328
4	3	4x3	0.469	1.132	0.191	0.506
6	2	6x2	2.156	1.076	0.790	25.774
6	3	6x3	1.625	1.074	0.563	4.292
6	4	6x4	1.563	0.908	0.309	0.931

2.3.1.3. VRS Tee Model

Tee fittings were simulated by using the BRANCH model as indicated in Table 2.1. Each branch component had three junctions, thus connecting three pipes as necessary. The K value for regular tees were calculated in the same way as was the case for elbows (Crane Corporation, 1988):

$$K = C f_T \quad (2.27)$$

Where C is 20 or 60 for the flow through the run and branch, respectively. Table 2.4 summarizes all regular tee loss coefficient values for several nominal pipe diameters that were used in the VRS model.

Table 2.4. Regular tee loss coefficient values.

Large diameter D_2 (in)	D_2 friction factor f_T	Flow through run K	Flow through branch K
4	0.017	0.340	1.020
4	0.017	0.340	1.020
4	0.017	0.340	1.020
6	0.015	0.300	0.900

Reducing tee loss coefficients (for BRANCH components 310, 330, 410 and 430) were calculated by adding the regular tee and contraction K values, depending upon the direction of the flow through the run or branch.

2.3.1.4. VRS Valve Model

The two-inch check valves (components 710 and 810) were simulated by using the VALVE model as indicated in Table 2.1. The VALVE functions as a junction between two pipes for the VRS model in specific. The minimum opening pressure is approximately 0.5 psi and the loss coefficient was calculated using a lift check valve coefficient of 600 and a pipe friction factor of 0.019 (Crane Corporation, 1988):

$$K = 600f_T = 11.4 \quad (2.28)$$

All ball valves (components 350 and 450) were also simulated using the VALVE model as previously described. However, the loss coefficient values were obtained by using the flow coefficient (C_V) specified by manufacturer's standards as follows (Crane Corporation, 1988):

$$K = \left(\frac{29.9D^2}{C_V} \right)^2 \quad (2.29)$$

The flow coefficient values for the four-inch and six-inch ball valves were 3129 gpm/psi and 7942 gpm/psi, respectively. The loss coefficients for the four-inch and six-inch ball valves were 0.024 and 0.019, respectively.

The single junction (SNGLJUN) was utilized to connect PIPE-600 to the tank component 900. The forward and reverse K values for the pipe exit were set to unity and 0.75, respectively.

2.3.1.5. VRS Air Compressor Model

The air compressor was simulated by using one TMDPVOL, one TMDPJUN, two SNGLVOL and one VALVE block as shown in Figure 2.6. This system was then connected to BRANCH 407, where air was injected under steady-state conditions.

2.3.1.6. VRS Pipe Nodalization

The nodalization process was carried out by using the L/D ratio, which was set to be greater than unity for numerical stability. Not all pipe volumes had the same length due to their characteristic diameter, hence $L > 0.3355$ ft for a four-inch pipe and $L > 0.5054$ ft for a six-inch pipe. Appendix B contains all the data pertaining to this ratio.

2.3.2. VRS Model Boundary Conditions

2.3.2.1. VRS Tank/Pump Model

The boundary condition for the tank/pump model was specified by using a combination of a TMDPVOL and a TMDPJUN. TMDPVOL-200 (tank) conditions were set with a constant pressure and temperature of 65 psi and 70°F, respectively. TMDPJUN-205 (pump) conditions were set to various mass flow rates as seen in Table 2.5, which were directly obtained from experimental results and are a function of the Froude numbers tested, being approximately 0.8, 1.0, 1.3 and 1.6.

Table 2.5. Summary of the simulated pump flow rates as a function of the Froude number.

q (gpm)	$\dot{m}_l$ (lb/sec)	V (4") (ft/s)	V (6") (ft/s)	Fr (4")	Fr (6")
105	14.540	2.646	n/a	0.805	n/a
125	17.310	3.151	n/a	0.959	n/a
168	23.265	4.234	n/a	1.288	n/a
208	28.804	5.242	n/a	1.595	n/a
294	40.713	n/a	3.265	n/a	0.809
400	55.392	n/a	4.442	n/a	1.101
500	69.240	n/a	5.553	n/a	1.376
582	80.596	n/a	6.464	n/a	1.602

The averaged flow rates (q) were obtained from the experimental results, and the mass flow rates ($\dot{m}_l$) were calculated by using the following expression:

$$\dot{m}_l = \frac{q \rho_l}{448.8 \frac{\text{gal}}{\text{ft}^3} \frac{\text{s}}{\text{s}}} \quad (2.30)$$

where ρ_l is the water density and its value corresponds to 62.15 lb/ft³ at 70°F.

Note that TMDPVOL-900 is modeled with the same boundary conditions as TMDPVOL-200, and in fact, simulate the same tank. However, RELAP5 only allows connecting one component to a TMDPVOL.

2.3.2.2. VRS Air Compressor Model

The boundary conditions for the air compressor model follow the same methodology as the tank/pump model, except that air is injected for 15 seconds at a specific time range. Table 2.6 and Table 2.7 show the air injection scheme used for the four-inch and 6-inch pipes to guarantee a minimum initial void fraction of seven-percent, at various Froude numbers. Many other initial void fractions were performed during the experiment, though this value was chosen to guarantee a sound comparison, since the initial void fractions between both pipes were similar. Even though the experimental initial void fractions were six and five-percent for the four-inch and six-inch pipes respectively, it was necessary to guarantee the previously mentioned void fraction value of seven-percent to account for a physical behavior not modeled by RELAP5 called *kinematic shock* (Westinghouse Electric Company, LLC, 2010). This phenomenon specifically occurs when the gas is transported into the downstream of the downturned elbow, resulting in a “waterfall” effect, where a vertically downward stratified flow pattern occurs. The void fraction or amount of air being transported into the bottom horizontal pipe highly depends on the kinematic shock location, and as a consequence, is a function of the vertical pipe length to pipe diameter (L/D) ratio. Assuming steady-state flow conditions, the void fraction decreases as it travels downwards through the vertical pipe, or as the L/D ratio increases (Marshall, 2003). Since the kinematic shock was indeed observed during the experiment and occurred typically at half the vertical pipe distance ($L/2D$) by allowing more air to travel downwards, then an extra quantity of void had to be added into the computational model to account for the amount of air being formed in the downcomer pipe.

Table 2.6. Air injection scheme for various Froude numbers in the four-inch pipe, yielding a minimum initial void fraction of seven-percent.

Injection Time (s)	Air Flow Rate (lb/s) - 4" pipe			
	Fr = 0.81	Fr = 0.96	Fr = 1.29	Fr = 1.60
0-15	0	0	0	0
16	0	0	5.00E-04	1.00E-03
17	0	5.00E-04	1.00E-03	2.00E-03
18	5.00E-04	1.00E-03	2.00E-03	3.00E-03
19	1.00E-03	2.50E-03	3.00E-03	4.00E-03
20-35	3.00E-03	3.30E-03	3.80E-03	4.50E-03
36	2.80E-03	3.00E-03	3.50E-03	4.00E-03
37	2.60E-03	2.00E-03	3.00E-03	3.00E-03
38	2.40E-03	1.00E-03	2.00E-03	2.00E-03
39	2.00E-03	5.00E-04	1.00E-03	1.00E-03
40	1.60E-03	0	5.00E-04	5.00E-04
41	1.20E-03	0	0	0
42	0	0	0	0

Table 2.7. Air injection scheme for various Froude numbers in the six-inch pipe, yielding a minimum initial void fraction of seven-percent.

Injection Time (s)	Air Flow Rate (lb/s) - 6" pipe			
	Fr = 0.81	Fr = 1.10	Fr = 1.38	Fr = 1.60
0-15	0	0	0	0
16	0	0	0	1.00E-03
17	1.00E-03	1.00E-03	1.00E-03	5.00E-03
18	3.00E-03	3.00E-03	5.00E-03	7.00E-03
19	5.00E-03	5.00E-03	7.00E-03	1.20E-02
20-35	7.80E-03	9.70E-03	1.20E-02	1.48E-02
36	5.00E-03	6.00E-03	6.00E-03	6.00E-03
37	3.00E-03	3.00E-03	3.00E-03	3.00E-03
38	1.00E-03	1.00E-03	1.00E-03	1.00E-03
39	0	0	0	0
40	0	0	0	0

2.3.3. VRS Model Thermal/Hydraulic settings

RELAP5 uses two different set of control flags that allow the calculation of specific thermal/hydraulic models (RELAP5/MOD3.2, Code Manual Volume II: User's Guide and Input Requirements, 1995). It is up to the user to use them accordingly depending upon the simulation being carried. The first set of control flags consist of the packed format tlpvbfe, which allows the processing of the following models:

t – Thermal front tracking model: used to improve the accuracy calculations when a warm fluid layer appears above a cold fluid.

l – Mixture level tracking model: used to calculate the void fractions (above and below level) and level velocity in a volume.

p – Water packing scheme: used to model a pressurizer.

v – Vertical stratification model: used to model a pressurizer.

b – Interphase friction model: used to model the pipe or rod bundle interphase friction.

f – Wall friction model: used to specify if the wall friction effects are to be accounted for.

e – Non-equilibrium model, used to specify the non-equilibrium or equilibrium model. This option is provided for the comparison between other codes.

The second set of control flags consist of the packed format efvcahs, which allows the processing of the following models:

e –modified *PV* (pressure-volume) term: used to specify if the *PV* term is to be applied.

f – Counter-current Flow Limitation (CCFL) model: used specifically for vertical volumes, gas-liquid phases and counter-current flow (liquid flowing down, gas flowing up).

v – Horizontal stratification model, used to model a BRANCH component.

c – Choking model: recommended to be used for modeling relief valves. Removal of the choking model may be recommended to avoid internal oscillations.

a – Abrupt area model: used when sharp edged area changes occur; recommended to be used in a BRANCH component.

h – Non-homogenous model: used to specify the non-homogeneous (two-velocity momentum equations) or homogenous (single-velocity momentum equation) options.

s – Momentum flux model: used in BRANCH components; specifies the use of the momentum flux in the BRANCH junctions.

Table 2.8 shows the summary of the control flags used in the main VRS model components, including the tank/pump, pipe, regular tees, check valves and ball valves. The letter ‘X’ is used to symbolize that the current model is being used. The letters ‘N-E’, ‘N-H’, ‘S’, and ‘A’ stand for *non-equilibrium*, *non-homogenous*, *smooth area change*, and *abrupt area change*, respectively.

Table 2.8. Summary of the control flags used for various VRS model components.

Control Flag	VRS Model Component				
	Tank/Pump	Pipe	Regular Tee	Check Valve	Ball Valve
t					
l					
p					
v		X			
b	Pipe Friction	Pipe Friction	Pipe Friction	Pipe Friction	Pipe Friction
f		X	X	X	X
e	N-E	N-E	N-E	N-E	N-E
e					
f					
v					
c				X	
a		S	A	S	S
h		N-H	N-H	N-H	N-H
s					

Table 2.9 shows the summary of the control flags used in the reducing tees of the VRS model. The listed reducing tees refer specifically to the BRANCH components 310 (four-inch upper tee), 410 (six-inch upper tee), 330 (four-inch lower tee) and 430 (six-inch lower tee). The large and small diameters mentioned in Table 2.9 refer to the main pipe connections (four or six-inch pipes) and the reduced void recirculation pipes (three or four-inch pipes) connections, respectively. The same letters apply as before, with the addition of the letters ‘H’, ‘D’ and ‘U’, which stand for *homogeneous equation*, downwards and upwards oriented junctions, respectively. Important differences lie between the different reducing tees and are worth mentioning for the sake of the VRS model. While the large diameters of 310/410 and 330/430 use the same control flags, the small diameters of 310/410 and 330/430 have one main distinction: the use of the ‘D’ and ‘U’ models. Specifically, the small diameter of 310 and 410 uses the downwards

oriented junction since it connects to the top of pipe components 720 and 820, respectively, which come from the bottom. In contrast, the small diameter of 330 and 430 uses the upwards oriented junction since this one connects to the bottom of pipe components 700 and 800, which are placed directly above the main lower pipe.

Table 2.9. Summary of the controls flags used for various VRS model reducing tees.

	VRS Model Component			
	310, 410 Reducing Tees	310, 410 Reducing Tees	330, 430 Reducing Tees	330, 430 Reducing Tees
Control Flag	Large Diameter	Small Diameter	Large Diameter	Small Diameter
t				
l				
p				
v				
b	Pipe Friction	Pipe Friction	Pipe Friction	Pipe Friction
f	X	X	X	X
e	N-E	N-E	N-E	N-E
e				
f		X		X
v		D		U
c				
a	A	A	A	A
h	H	N-H	H	N-H
s				

Other control flag configurations were attempted during the sensitivity analysis of the VRS model. However, the decision on using this specific arrangement was based both on the RELAP5 code recommendation for numerical stability, and on results that yielded most realistic behavior.

2.3.3.1. VRS Valve Model

The valve model only uses the packed format *efvcahs*, where the choking model (c) is only used for the check valve, recommendation done by RELAP5 for relief valves. All other process models were not used on both check and ball valves.

2.4. Fluid Properties

The fluids used in the VRS model are water for the liquid phase and air (non-condensable) for the gas phase. Both fluids were set at a temperature of 70°F, and at different pressures depending on the component used. RELAP5 automatically calculates all fluid properties once the types of fluids, temperatures and pressures have been specified.

2.5. Simulation Assumptions

The VRS model, built in RELAP5, was created under the following assumptions:

- All simulations happen on the discharge side of the pump, rather than on the suction side. These simulations are intended to be benchmarked with the experimental results, which were also carried on the discharge side of the pump.
- Air injection occurs when the main flow is steady-state, assuming the pump has been running for a certain amount of time.

- The Froude number parameters, which are meant to describe the water velocities, are assumed to be referenced to the main four and six-inch pipes, with water occupying the entire cross-section of the pipe.
- The VRS tank is modeled as a water reservoir, having a constant pressure.
- The VRS pump is modeled with a constant supply of water, rather than using a pump curve, for better code handling.
- The kinematic shock phenomenon is replaced by adding a slightly greater amount of air than that recorded during the experiment.

Chapter 3. SIMULATION SCENARIOS, RESULTS AND DISCUSSION

3.1. Void Recirculation Experiment

3.1.1. Experiment Description

The Void Recirculation System, Figure 3.1, is the experimental setup used to validate the results from the RELAP5 simulation. Unlike Figure 1.3 where the same setup was shown for the suction side of the pump, Figure 3.1 shows the experimental setup on the discharge side of the pump.

Figure 3.1. Experimental setup of the Void Recirculation System.

The water coming from the six-inch trash pump enters the upper main pipe before station one and continues its path through stations two, three and four, where it ultimately discharges into the water tank. Air was injected (after the water flow reached steady state) for a period of 15 seconds, through a 3/8-inch flexible hose. The air injection was located at the top section of the upper main pipe, approximately two feet to the left from

station one, using an air compressor as previously described in Section 2.3.1. The air follows the path along stations one through four, with the exception that the majority of the air recirculates upwardly through the void recirculation pipe. The green colored pipe and arrows denote the void recirculation pipe and air recirculation path, respectively. Specifically, only air recirculates between stations two and three. A two-inch check valve, with a minimum opening pressure of 0.5 psi, was located on the void recirculation pipe (VRP) to prevent downward water flow, and to allow air accumulation on the bottom section of the VRP. Hence, the check valve allowed only upwards flow. The experimental setup, Figure 3.1, applies for the tested branches: four-inch and six-inch diameter pipes. A thorough dimensional description of the VRS, for both four-inch and six-inch branches, can be seen in Appendix A – VRS Piping Drawings. It is important to note that these figures only show lower pipe configurations of 4x4x3-inch and 6x6x4-inch. The words ‘pipe configuration’ are meant to describe how the different reducing tees were used to connect each respective nominal pipe size. Figure 3.2 shows a picture of the different bottom pipe configurations that were used during the VRS experiment, ranging from four-inch to eight-inch pipes. Since the objective of the experiment was to test for pipe configurations that removed air more efficiently from the main pipe, the present study focuses on the 4x4x3-inch and 6x6x4-inch pipe configurations in view of the fact that these yielded a higher air removal rate with respect to the other pipe configurations tested.

Figure 3.2. Lower pipe configurations used during the VRS experiment.

The main parameters controlled during the VRS experiment were initial void fraction and main pipe flow rate. Void fraction measurements were determined visually using square level rulers with 1/8-inch measurement resolution, located at stations one through four, where station one was used to determine the initial void fraction. The initial void fractions during the VRS experiment varied between three and 13 percent for the different pipe configurations tested. The initial void fraction to be analyzed under the present study is approximately seven percent for both pipe configurations 4x4x3-inch and 6x6x4-inch. The void fraction value of seven percent was carefully chosen since it appears in both pipe configuration results, allowing easy comparison. The maximum allowable void fraction in station four of the VRS model and test fixture is five percent

for pipe diameters less than 12 inches. This five percent void fraction value is based on nuclear industry acceptability and on-going research (Institute of Nuclear Power Operations, 2010). Flow rate measurements were determined electronically using a turbine paddle flow meter, located on the main six-inch pipe after the pump as depicted in Figure 2.6. Flow rate values were then converted to Froude numbers to allow easy comparison between the different pipe diameters tested. A summary of the different flow rates tested for both pipe branches can be seen in Table 2.5 for further reference. Three different trials were measured with the same initial void fraction and Froude number. The void fraction recorded at each station was a visual average for the period of time of each trial (approximately two minutes or 120 seconds). Hence, only three void fraction values taken from each trial were reported for each scenario. Even though the experimental results were insufficient for a thorough statistical analysis, it provides an insight of the values to be expected at each station and will be used to validate the numerical results obtained from RELAP5.

The experiment setup was chosen to be in this specific way for two main reasons: first, to have better flow rate control and second, to avoid the rather complicated vacuum running conditions. Even though air behaves differently under suction and discharge conditions, the recirculation behavior was the main objective to prove that the VRS device worked properly.

3.1.2. Experiment Observations

There are several experimental observations that need to be reported for the sake of the VRS simulation validation. All observations reported under this section are based on flow regime patterns seen in all tested branches and are accompanied by pictures taken during the experiment. There are five main sections for which the flow behavior is of great interest: upper main pipe, vertical downward flow pipe or downcomer, lower elbow, lower tee and void recirculation pipe. These sections will be used to validate the results from the RELAP5 simulation. Figure 3.3 shows all the sections of experimental interest for the VRS, including the main five sections previously described, which can be seen in boxed texts.

Figure 3.3. Sections of experimental interest for the Void Recirculation System.

3.1.2.1. Upper Main Pipe Observation

The flow regime observed in all upper main pipe branches, comprising in the four-inch and six-inch pipes, was a horizontal stratified flow regime. Figure 3.4 is a picture taken on the opposite side of the pipe between the upper tee and upper elbow, showing the nature of the flow regime encountered at all tested flow rates and initial void fractions. In this picture the main pipe, square level rulers to measure the void fraction and the horizontal stratified flow regime can be appreciated. The horizontal stratified flow regime is composed of the air and water phases, which can be seen in the upper and lower parts of the main pipe, respectively.

Figure 3.4. Horizontal stratified flow regime observed in the four and six-inch pipes.

The bubbles seen near the center of the main pipe (right side of picture) originate from the void recirculation pipe, which is ultimately connected to the bottom side of the upper tee. The observed air in this picture is in fact the air that has been removed at the lower tee and proves that the VRS works properly. The bubbles, located near the center of the main pipe, eventually rise to the top of the pipe due to their lower density. Since air is being added from the bottom side of the upper tee, this specific process creates flow instability, or waves, due to variations in void fraction at different sections of the pipe. In other words, the observed flow regime is in fact wavy horizontal stratified flow and will become important as the simulation results are explained.

3.1.2.2. Downcomer Observation

The flow regime observed in all downcomers was bubbly flow as seen in Figure 3.5, which is a picture taken before the six-inch lower elbow. In some cases, slugs of air were observed travelling upwards in the opposite direction of the main flow path. This behavior was possibly due to the coalescence of air bubbles at the lower elbow, followed by an increase in buoyancy that ultimately was larger than the water inertia force. The coalescence of bubbles at the lower elbow is possibly due to a velocity gradient generated with a sharp turn in direction, hence leading to a local pressure gradient.

Figure 3.5. Downward bubbly flow regime observed in the four and six-inch pipes.

3.1.2.3. Lower Elbow Observation

The flow regimes observed after the lower elbow for all tested pipe branches varied between wavy horizontally stratified, slug and bubbly flow. Figure 3.6 shows the wavy horizontal stratified flow observed at one instant of time, with bubbly flow in the water phase. These bubbles, due to their lower density, eventually rise and help generate waves downstream. Figure 3.7 shows a combination between bubbly and slug flow in a short length of pipe and at a later instant of time than Figure 3.6. The bubbly flow is shown to the left, immediately after the lower elbow and the slug flow is shown to the

right of the picture accompanied by the tail of the bubble. The behavior variation may be due to changes in velocity gradients and void fraction quantities, and is an indication that the air bubble is slowly being transported in the direction of the main flow.

Figure 3.6. Wavy horizontal stratified flow observed in the four and six-inch pipes.

Figure 3.7 Bubbly and slug flow observed in the four and six-inch pipes.

Finally, it was observed that in many cases an air bubble would form, immediately after the lower elbow, with a defined bubble head. This bubble would move back and forth for a period of time, with a severe change in void fraction but no net velocity, until water broke the air bubble by allowing it to move in the direction of the main flow. When the breaking process happened, the air bubble accelerated until it reached the velocity of the water. This phenomenon can be clearly depicted in the following section and will become important for simulation validation.

3.1.2.4. Lower Tee Observation

The flow regimes observed at stations three (before lower tee) and four (after lower tee) varied between bubbly and slug flow, but were significantly different in void fraction quantity since the lower tee removed the majority of the air coming from station three. Figure 3.8 shows a picture taken at station three at one instant of time, with a void fraction of approximately 50 percent. Even though the flow regime in Figure 3.8 seems to be wavy horizontally stratified, the air bubbles seen to the right of the picture is an indication that the bubble head is nearby. Thus the flow regime at this moment of time is in fact slug flow. The lower tee, though not shown in Figure 3.8, is located to the right of the square level ruler.

Figure 3.8. Slug flow observed at station three in the four and six-inch pipes.

Figure 3.9 shows the same picture as before taken at a later instant of time where the bubble head, previously mentioned, is clearly depicted and is proof of the bubble slowly traveling in the direction opposite of the main flow path (i.e. right to left). The void fraction seen to the left of the picture where the slug is present is approximately 30 percent. However, the void fraction present to the right of the picture was impossible to measure with this square level ruler since the regime was bubbly flow.

Figure 3.9. Wavy horizontal stratified and bubbly flow transition observed at station three in the four and six-inch pipes.

From Figure 3.8 and Figure 3.9, it was concluded that the void fraction decreased locally each time the bubble was moving in the direction opposite of the main flow path,

implying that the air velocity would range between zero and negative values. In contrast, the void fraction increased locally whenever the bubble traveled in the direction of the main flow path, implying that the air velocity would range between zero and positive values. This behavior supports the discussion provided in the previous section (3.1.2.3), where the bubble moves back and forth for a period of time, until there is enough void fraction with respect to the main flow to disrupt the air bubble, allowing it to travel in the direction of the main flow path.

The flow regime observed at station four was mainly bubbly with little amount of void fraction as seen in Figure 3.10. Occasionally, slugs of air were observed with approximately 20 percent void fraction, but only for a short period of time. This behavior may be due to a flow discontinuity generated by the lower tee, which will be further discussed in the next section.

Figure 3.10. Bubbly flow observed at station four in the four and six-inch pipes.

3.1.2.5. Void Recirculation Pipe Observation

The flow regimes observed during the experiment at the void recirculation pipe varied constantly between upwards slug and upwards bubbly flow. This behavior was characteristic in the pipe section immediately before the two-inch check valve. It is worth mentioning that no total mass flow rate was seen through the VRP even though the experiment had already started, since the check valve only allowed upwards flow. Figure 3.11 shows the upwards slug flow observed when the first amount of air was transported between station three and the lower tee.

Figure 3.11. Upwards slug flow observed at the VRP for the four and six-inch pipe configurations.

The head of the bubble, which takes the form of a bullet shape, matches the description of the Taylor bubbles seen in Figure 2.3, and can be seen towards the top of the picture. The bubble head is followed by the bubble body seen in the middle of the picture, which is occupying nearly 90 percent of the inner pipe diameter. This slug of air forces the water to move sideways towards the wall (thin water wall formation) and downwards, until no more slugs are present, for which at this time bubbly flow occurs as shown in Figure 3.12. The flow regime in this section of pipe varied between slug and bubbly

flow, thus matching the description of a Taylor Bubble Train flow regime, as seen in Figure 3.13. This behavior was typical for Froude numbers of 0.8, 1.0 and 1.3.

Figure 3.12. Upwards bubbly flow observed at the VRP for the four and six-inch pipe configurations.

Figure 3.13. Taylor Bubble Train Flow Regime (Flow Regime Sample Movies).

It is possible that the formation of the Taylor bubble train flow regime at the intersection between the VRP and lower tee causes a discontinuity of the air-water flow coming from station three. This discontinuity may be a reason for why the air bubble in station three moves back and forth, and why there are small slugs of air at station four throughout the experiment.

Air recirculation through the VRS stopped after approximately two minutes of testing at the highest flow rates for both four and six-inch branches, which correspond to a Froude number of 1.6. Hence, after two minutes, very little to no air was seen in stations one through four, but only a certain amount of air accumulated before the check valve as seen in Figure 3.14. Recall that air injection occurred for 15 seconds at the beginning of the experiment, thus no air was added at the time this photograph was taken. Since this amount of air was not sufficient to open the check valve, then this air bubble would settle indefinitely. Furthermore, this amount of air captured before the check valve was the total air successfully removed in the VRS at the highest flow rate.

In conclusion, the amount of air recirculated was greater at Froude numbers approximately up to 1.3, since the check valve was continuously opening and closing throughout the experiment. This makes sense because the water travels relatively slow to allow a higher amount of upwards air flow. Conversely, a lower amount of air was removed at the highest flow rate, corresponding to a Froude number of 1.6. This also makes sense since the water travels relatively fast to carry more air past the lower tee and to station four, where it ultimately ends in the tank.

Figure 3.14. Air settling before the check valve in the six-inch branch.

3.2. Description of Simulation Scenarios

The simulations to be considered in the present study will apply to those selected under Section 3.1. More precisely, the pipe configurations 4x4x3-inch and 6x6x4-inch will be simulated in RELAP5, analyzed and validated against the experimental Void Recirculation System results. Table 3.1 shows the list of simulation scenarios to be considered for the RELAP5 VRS model. There are a total of eight simulation scenarios: four for the 4x4x3-inch and 6x6x4-inch pipe configurations, respectively. All eight scenarios have different volumetric flow rates and thus mass flow rates. However, only four different Froude numbers are analyzed for both pipe configurations and are approximately 0.81, 1.00, 1.30 and 1.60. These values correspond to the tested

volumetric flow rates in the VRS experiment. Air was injected following a specific scheme as shown in Table 2.6 and Table 2.7 to ensure a minimum initial void fraction of seven percent. Each simulation scenario was modeled for a period of 150 seconds. The code built in RELAP5 for simulation scenario one can be seen in Appendix C – VRS RELAP5 Code for further reference.

Table 3.1. List of simulation scenarios for the RELAP5 VRS model.

Scenario	Main Pipe Diameter (in)	Pipe Configuration (in)	q (gpm)	$\dot{m}_l$ (lb/s)	Fr
1	4.026	4x4x3	105	14.5	0.81
2	4.026	4x4x3	125	17.3	0.96
3	4.026	4x4x3	168	23.3	1.29
4	4.026	4x4x3	208	28.8	1.60
5	6.065	6x6x4	294	40.7	0.81
6	6.065	6x6x4	400	55.4	1.10
7	6.065	6x6x4	500	69.2	1.38
8	6.065	6x6x4	582	80.6	1.60

3.3. Convergence Test

The convergence test for the VRS model consists in showing time and grid independence. For both tests, only the void fraction of simulation scenario one, at station three, will be used to evaluate the independence of the model built in RELAP5. Station three was chosen to be of particular interest since it is the section that contains the largest amounts of air to be recirculated through the VRS. Table 3.2 shows the list of convergence tests to be done for the VRS model. The time independence test consists in evaluating the void fraction at station three, using 32 nodes (finest mesh), for the following time steps: 1.0×10^{-2} , 1.0×10^{-3} , and 1.0×10^{-5} seconds. An average relative error, taken throughout the entire simulation time will be used to report time independence.

Table 3.2. List of convergence tests for the RELAP5 VRS model.

Simulation Scenario	Test	Time Step Criterion (seconds)	Mesh Size Criterion (No. of Nodes)
A	Time Independence	1×10^{-2}	32
B		1×10^{-3}	32
C		1×10^{-5}	32
D	Grid Independence	1×10^{-3}	11
E		1×10^{-3}	20
F		1×10^{-3}	32

The grid independence test consists in using a constant time step of 1×10^{-3} seconds and changing the number of nodes in the VRS as follows:

Fine mesh, $N_1 = 32$ nodes

Medium mesh, $N_2 = 20$ nodes

Coarse mesh, $N_3 = 11$ nodes

It is important to note that the number of nodes was edited only for pipe component 320, which encompass stations two, the main pipe downcomer and station three (which is of highest interest). The Richardson extrapolation (RE) method (Celik, Ghia, Roache, & Freitas, 2008) will be used to estimate the discretization error and to determine grid convergence for the void fraction solution at station three.

3.3.1. Time Independence Test

Figure 3.15 shows the void fraction behavior for simulation scenario one at station three for different time steps. The time steps 1.0×10^{-2} , 1.0×10^{-3} , and 1.0×10^{-5} seconds can be depicted in dashed, solid and dotted lines, respectively.

Figure 3.15. Void fraction behavior for scenario one at station three for different time steps.

During the first 65 seconds, all solutions behave similarly with an oscillatory motion, which will be later explained under the results and discussion section. The solution for the largest time step begins to be off-phase with respect to the other two solutions after 65 seconds. This behavior might be due to numerical calculations within RELAP5, since the oscillation pattern seems to be the same throughout the simulation time. The relative error was calculated using the following formula:

$$e_a^{AB} = \left| \frac{VF_B - VF_A}{VF_B} \right| \quad (3.1)$$

where VF is the void fraction at station three at a particular time, and the subscripts A and B correspond to the largest (1.0×10^{-2} seconds) and intermediate (1.0×10^{-3} seconds) time steps, respectively. The relative error of the void fraction was computed for every second up to 125 seconds, and an average relative error was calculated for the entire simulation time. The average relative error between convergence scenarios A and B was approximately 264%. This high value is a consequence of the off-phase behavior between these two solutions. The void fraction relative error between the intermediate (1.0×10^{-3} seconds) and smallest time steps (1.0×10^{-5} seconds) was found by using the following:

$$e_a^{BC} = \left| \frac{VF_C - VF_B}{VF_C} \right| \quad (3.2)$$

where the subscripts B and C correspond to the intermediate and smallest time steps, respectively. The average relative error between these convergence scenarios was found to be approximately 35%. This comparatively low value makes sense because, unlike the off-phase behavior between scenarios A and B, the time step solutions between scenarios B and C are closely in phase, thus leading to a smaller relative error. In terms of computational time, scenarios A, B and C took approximately 2 minutes, 30 minutes and 2 days, respectively. Because a greater relative error difference was obtained by using the intermediate time step of 1.0×10^{-3} seconds when compared to total computational time, then it was decided to use this specific time step for all simulation scenarios. In

addition, the results obtained for this particular time step demonstrate good convergence behavior with respect to the smallest time step.

3.3.2. Grid Independence Test

Figure 3.16 shows the void fraction behavior for simulation scenario one at station three for different mesh sizes. The coarse, medium and fine meshes can be depicted in dashed, solid and dotted lines.

Figure 3.16. Void fraction behavior for scenario one at station three for different mesh sizes.

In this graph, the smoothest void fraction behavior can be appreciated for the coarse mesh when compared to the medium and fine meshes. However, the coarse mesh solution is in fact the least accurate since it does not describe the physical behavior of two-component

flow for the VRS experiment. The medium and fine meshes have a similar oscillating behavior, with the exception that the solutions are not always in phase throughout the entire simulation time. Table 3.3 shows the discretization error results for scenarios D, E and F, which were based on the RE method.

Table 3.3. Discretization error results based on the RE method.

Parameter	Value
N_1, N_2, N_3	32, 20, 11
r_{21}	1.37
r_{32}	1.48
p	3.75
e_a^{2l}	192%
e_{ext}^{2l}	135%
GCI_{fine}^{2l}	74%

The grid refinement factor, r , is a ratio of coarse to fine mesh and is a function of the number of nodes and the total pipe area of interest. This parameter was used to calculate the apparent order, p using the following expressions (Celik, Ghia, Roache, & Freitas, 2008):

$$p = \frac{1}{\ln(r_{21})} \left| \ln \left| \frac{\varepsilon_{32}}{\varepsilon_{21}} \right| + q(p) \right| \quad (3.3)$$

$$q(p) = \ln \left(\frac{r_{21}^p - s}{r_{32}^p - s} \right) \quad (3.4)$$

$$s = 1 \cdot \text{sign} \left(\frac{\varepsilon_{32}}{\varepsilon_{21}} \right) \quad (3.5)$$

where $\varepsilon_{32} = VF_3 - VF_2$, $\varepsilon_{21} = VF_2 - VF_1$ and the subscripts 1, 2, and 3 correspond to the fine, medium and coarse meshes, respectively. These values, along with the apparent order were calculated at each second for 125 seconds. Then, an average apparent order was calculated for the entire simulation time, in which the value was found to be approximately 3.75. This value was not in agreement with the formal order of the scheme used in RELAP5, which was unity. According to Celik et al. (2008), the RE method does not work when ε_{32} or ε_{21} is approximately zero, which in this case, the majority of the values were very close to zero. In addition, the authors suggest that these results might be an indication of an oscillatory convergence or that an exact solution has been achieved. For the particular VRS model, it seems that an oscillatory convergence behavior was attained by looking at Figure 3.16, which might explain the reason why the apparent order is not in agreement with the formal order of the scheme used in the simulation. The approximate relative error, extrapolated relative error and the fine-grid convergence index between medium and fine meshes were calculated using the following expressions respectively (Celik, Ghia, Roache, & Freitas, 2008):

$$e_a^{21} = \left| \frac{VF_1 - VF_2}{VF_1} \right| \quad (3.6)$$

$$e_{ext}^{21} = \left| \frac{VF_{ext}^{12} - VF_1}{VF_{ext}^{12}} \right| \quad (3.7)$$

$$GCI_{fine}^{21} = \frac{1.25e_a^{21}}{r_{21}^p - 1} \quad (3.8)$$

Each of these values were then averaged for the simulation time of 125 seconds. The relative error was found to be 192%, while the extrapolated relative error was 135%. The fine-grid convergence index was found to be approximately 74%. These high values are associated with the off-phase behavior seen in Figure 3.16, in addition of the high apparent order $p = 3.75$. More precisely, the location of station three chosen for all convergence scenarios slightly varied between each other due to mesh refinement. Numerical results showed that the void fraction tends to drastically change from node to node for this VRS model in specific. This implies that two-component flow is extremely sensitive to pipe location and time.

As a rule of thumb, GCI should be higher than e_{ext} at an apparent order of unity. Because the original apparent order $p = 3.75$ yielded a lower GCI value with respect to e_{ext} , then it was decided to recalculate the discretization error parameters by using a modified apparent order. Both apparent orders of unity and two were tested, but it was found that the former value yielded extremely high discretization errors. Table 3.4 summarizes the results for the modified discretization error using $p = 2.00$, which is the closest value to the formal order of the scheme used in RELAP5. In this case, the relative and extrapolated errors were approximately 192% and the GCI is 271%, which is greater than e_{ext} .

Table 3.4. Modified Discretization error results based on the RE method, using $p = 2.00$.

Parameter	Value
p	2.00
e_a^{2l}	192%
e_{ext}^{2l}	191%
GCI_{fine}^{2l}	271%

Even though the discretization errors continue to be high, the fine mesh solution demonstrates good convergence behavior, and more importantly, numerically describes the behavior linked with reality. The simulation scenarios analyzed in the present study use the finest mesh described above.

3.4. Simulation Validation, Results and Discussion

This thesis analyzes a simulation of two-component (air and water) flow in a Void Recirculation System, where the main parameters to be considered are mass flow rates and void fraction at stations one through four, according to Figure 3.1. Experimental results are available from VRS tests carried at Cal Poly State University (Daza, Fong, Rosas, & Wong, 2009) and will be used to validate the VRS model developed in RELAP5. The purpose of analyzing mass flow rates obtained from the simulation results is to prove that the VRS model works properly, by showing a net positive upwards flow through the void recirculation pipe. The purpose of analyzing the void fraction is to describe the parameter's behavior at all stations with respect to time and to validate the numerical results to the VRS experiment. The simulation scenarios to be analyzed

assume a time step of 1.0×10^{-3} seconds with the finest mesh size as described in the convergence test section.

3.4.1. Mass Flow Rate Analysis

The mass flow rates of the VRS model for stations one, two, four and the void recirculation pipe, for simulation scenario one (4x4x3-inch, $Fr = 0.81$) can be seen in Figure 3.17. The mass flow rate in station one behaves constantly with respect to the other sections of interest at a value of 14.5 lb/s. This behavior makes sense since there is a constant source of water and air passing through station one. Air was injected between 20 and 35 seconds, where mass flow rate maximums can be seen for stations one, two and four. Even though air has not yet arrived at station four, the peaking behavior is the result of the mass conservation being calculated in RELAP5, since air is being added.

Figure 3.17. Mass flow rate behavior for simulation scenario one: 4x4x3-inch, $Fr = 0.81$.

The oscillating behavior seen at stations two, four and the recirculation pipe is mainly due to the check valve open/close operation. Station's two mass flow rate oscillates between 12 and 30 lb/s during the first 65 seconds of the simulation time, but only after air was injected. The wide oscillating range at station two is a result of air being recirculated upwards through the VRP, which is discharged into the upper tee and ultimately transported into station two. The mass flow rate fluctuation decreases as time increases and the frequency of the oscillation decreases as well. This behavior is due to a lower quantity of air being recirculated through the VRP since a fraction of the recirculated air has been transferred to station four, where it ultimately exits the VRS by

going back to the tank. In contrast, station four shows a lower oscillating mass flow rate range (7 to 22 lb/s) with respect to station two since there is a much lower quantity of air being transported in this pipe section. This explanation will become more apparent during the next section, where void fraction behavior is discussed.

The oscillating behavior in the recirculation pipe, which is a pipe volume located immediately before the check valve, can be better explained in Figure 3.18. This figure shows a comparison between the mass flow rate and void fraction at the VRP. The mass flow rate, depicted in the solid line, can be read from the primary vertical axis on the left. The void fraction, depicted in the dashed line, can be read from the secondary vertical axis to the right.

Figure 3.18. Mass flow rate and void fraction behavior at the recirculation pipe, for simulation scenario one: 4x4x3-inch, $Fr = 0.81$.

The mass flow rate varies between -3 and 10 lb/s, where the oscillating behavior decreases as time increases. The void fraction ranges between 0.3 and 1.0 for approximately 75 seconds after air has been injected and later decreases towards the end of the simulation. Note that the decreasing behavior occurs in both mass flow rate and void fraction parameters as time increases, implying that the quantity of air recirculating through the VRP is constantly decreasing due to a portion of air being transported to station four. This behavior was also observed during the experiment as was described in Section 3.1.2.5 for Froude numbers up to 1.3. Mass flow rate maximum peaks occur when the majority of the air has passed through the check valve, resulting in a minimum void fraction peak. On the other hand, mass flow rate minimum peaks occur when the air accumulates before the check valve opens. Furthermore, the negative mass flow rate peaks are an indication that the water is being forced down, by allowing the accumulation of air until enough pressure is built to open the check valve. The simulation flow regimes for the VRP indicate a variation between slug and annular mist. The numerical results for scenarios four and eight, which had the highest Froude number simulated of 1.6, indicated that recirculation ceased towards the end of the simulation by showing zero mass flow rate and a void fraction of unity for the VRP. This settling behavior can be seen in Figure 3.19, which is a plot comparison between the mass flow rate and void fraction of the VRP with respect to time, for simulation scenario eight (6x6x4-inch, $Fr = 1.60$). This behavior makes sense since at higher Froude numbers inertia forces are high enough to transport the air bubbles past the lower tee and into station four, thus leading to a lower net amount of air being recirculated through the VRP. Section 3.1.2.5 describes a similar behavior encountered during the experiment for a Froude number of 1.6.

Specifically, Figure 3.14 resembles the same exact air settling behavior towards the end of the experiment trial.

Figure 3.19. Mass flow rate and void fraction behavior at the recirculation pipe, for simulation scenario eight: 6x6x4-inch, $Fr = 1.60$.

The oscillating mass flow rate behavior seen in simulation scenario one was common for all eight scenarios, and the results are summarized in Appendix D.1. **Mass Flow Rate Results** An important difference between the pipe configurations 4x4x3-inch and 6x6x4-inch is discussed below. The simulation flow regime for stations one, two and four (for all scenarios) were horizontally-stratified flow for the majority of the simulation time. Bubbly flow was reached when the majority of the air had exited the system, usually at high Froude numbers of 1.3 and 1.6.

One important difference seen in scenarios four (4x4x3-inch, $Fr = 1.60$) through eight (6x6x4-inch, $0.81 \leq Fr \leq 1.60$), in addition of the oscillating behavior, was the fact that there was a steadier amount of air passing through the recirculation pipe. This effect can be clearly seen in Figure 3.20, where the mass flow rate for stations one, two, four and the recirculation pipe are plotted versus time. The steady behavior was a consequence of the check valve being continuously open for a period of time, which occurred approximately between 35 and 85 seconds for this scenario in particular. By steady, it is meant that the oscillating behavior did not occur as drastic as was the case for scenario one. Stations two and four were also affected by this constant source of air coming from the VRP, but continued to oscillate after 85 seconds, once lower amounts of air were captured in the VRP.

Figure 3.20. Mass flow rate behavior for simulation scenario five: 6x6x4-inch, $Fr = 0.81$.

More important than the check valve operation, the steady behavior in the VRP for scenario four (4x4x3-inch, $Fr = 1.60$) was probably caused by a higher Froude number, which ultimately allows the air to travel faster throughout the system, thus feeding a more constant amount of air from station three to the VRP. The mass flow rate through the VRP in simulation scenarios six (6x6x4-inch, $Fr = 1.10$) and seven (6x6x4-inch, $Fr = 1.38$) presented a steady behavior for a longer period of time with respect to scenarios five (6x6x4-inch, $Fr = 0.81$) and eight (6x6x4-inch, $Fr = 1.60$). It is possible that the Froude numbers represented in simulation scenarios six and seven are in near-perfect combination with respect to the existing amount of air to not allow many discontinuities

at the lower tee, resulting in a steadier upwards air flow. The fact that scenarios five through eight had a steady mass flow rate behavior through the VRP, which can be depicted in Figure D.5 through Figure D.8, was probably due to a higher cross-sectional amount of air in the six-inch pipe, when compared to the four-inch pipe. For example, a ten percent void fraction value in the four and six-inch pipes correspond to gas cross-sectional areas of 1.276 in^2 and 2.893 in^2 , respectively. Higher gas cross-sectional areas infer that higher amounts of air are being carried throughout the system, which in turn can prevent bubble discontinuities by allowing the air to have more surface area. This hypothesis could be the explanation for why the mass flow rate, and thus the void fraction did not oscillate as drastically as was the case for scenarios one through three, and it is strongly recommended to do a more in depth analysis of this behavior. Perhaps an analysis of the Weber number influence in horizontal flows could be performed since this parameter compares the inertial to surface tension forces.

In short, the VRS numerical results obtained from the simulation for mass flow rate, VRP void fraction and flow regime behavior seem to represent the physical behavior observed during the experiment (Section 3.1.2.), thus supporting the functionality of the VRS model.

3.4.2. Void Fraction Analysis

The void fraction analysis will focus on stations two, three and four, which are part of the main piping system. The purpose of analyzing the void fraction at these sections is to show the air removal effectiveness between stations three and four, and to

prove that the VRS model in RELAP5 works properly with respect to the experimental observations provided in Section 3.1.2.4. In addition, the void fraction in the pipe volume after the lower elbow will be briefly discussed. The purpose of analyzing the void fraction in this section is to show the backward and forward motion of the air bubble with respect to the experimental observations provided in Section 3.1.2.3.

3.4.2.1. Main Pipe Void Fraction

The void fraction behavior, for simulation scenario one (4x4x3-inch, $Fr = 0.81$), at stations two, three and four can be depicted in Figure 3.21. In this graph, the oscillating behavior is present, as was the case for the mass flow rate behavior discussed in the previous section. This particular behavior was also due to the check valve open/close operation, which eventually affects the entire VRS model. The air injection procedure can be clearly reflected in station two at 20 seconds, where a steady line can be seen for approximately 10 seconds until the void fraction starts to oscillate.

Figure 3.21. Void fraction behavior for simulation scenario one: 4x4x3-inch, $Fr = 0.81$.

As time advances, the void fraction at station two approaches an approximate value of 0.2, indicating that air is constantly being fed from the VRP and thus, recirculation happens indefinitely. This behavior was also common for stations three and four, with the exception that station three shows a greater oscillation, which is possibly due to the discontinuities present at the lower elbow and lower tee. A void fraction peak value of approximately 0.6 was the result of injecting air for a period of 15 seconds. Then, the void fraction started to decrease following an oscillatory motion until recirculation occurred (approximately after 75 seconds). At this time, the void fraction ranged between the extreme values of 0.05 and 0.4. More importantly, the maximum void fraction in station four occurred at approximately 0.3, but rapidly decreased to values less than 0.05, which is the maximum allowable void fraction accepted by the industry for

pipes less than 12 inches. The peaking behavior at station four was normal because of the high initial amount of air coming from station three. The pipe configurations 4x4x3-inch and 6x6x4-inch have a limited capacity to take large amounts of air, which explains this initial peaking behavior. Nonetheless, the majority of the air at station three, which is the most critical location in the VRS, was removed and recirculated throughout the system. The void fraction seen at station four is the amount of air that was not recirculated through the VRP, which ultimately returns to the tank. Table 3.5 shows the numerical results for the average percent air removed between stations three and four, for all simulation scenarios. The average amount of air for each station was measured as void fraction, and the average percent air removed for all scenarios was greater than 88%, which is a highly effective air removal value. The values were averaged for the period of time until station four contained less than one percent void fraction. The percent air removed was calculated using the following expression:

$$\text{Percent Air Removed} = 1 - \frac{\text{Void Fraction at Station 4}}{\text{Void Fraction at Station 3}} \quad (3.9)$$

Table 3.5. Numerical results for the average percent air removed between stations three and four.

Scenario	Pipe Configuration (in)	Fr	Void Fraction Station 3	Void Fraction Station 4	Percent Air Removed
1	4x4x3	0.81	0.266	0.0318	88.0%
2	4x4x3	0.96	0.237	0.0250	89.4%
3	4x4x3	1.29	0.273	0.0467	82.9%
4	4x4x3	1.60	0.292	0.0309	89.4%
5	6x6x4	0.81	0.422	0.0221	94.8%
6	6x6x4	1.10	0.350	0.0202	94.2%
7	6x6x4	1.38	0.309	0.0278	91.0%
8	6x6x4	1.60	0.218	0.0260	88.1%

The main reason why air recirculates indefinitely through the VRP is because of the relatively low Froude numbers with respect to the existing amount of air in the system. At low Froude numbers, air and water travel slower, which creates flow discontinuities between the lower elbow and lower tee. Figure 3.22 shows a comparison between the slip ratio and void fraction for simulation scenario one (4x4x3-inch, $Fr = 0.81$), at stations three and four. The purpose of showing this graph is to present the contrast of flow behavior between stations three and four. Solid lines are used to measure the slip ratio seen on the primary vertical axis to the left; and dashed lines are used to measure the void fraction on the secondary vertical axis to the right. Positive and negative slip ratios suggest that the flow is co-current and countercurrent, respectively. At the beginning of the simulation, and up to 75 seconds, the slip ratio at station three drastically varies between approximately -0.5 and 1.25. However, the slip ratio decreases towards an average value of zero at the end of the simulation time, as the void fraction continues to vary indefinitely between 0.05 and 0.4.

Figure 3.22. Slip ratio and void fraction behavior at stations three and four, for simulation scenario one: 4x4x3-inch, $Fr = 0.81$.

Note that slip ratio continues to oscillate between positive and negative values even towards the end of the simulation. This behavior suggests that air bubbles are being continuously recirculated through the VRS, but more importantly, shows the forward and backward motion of the air bubbles. Maximum slip ratio and void fraction values occur at the same time, meaning that the largest possible amounts of air continue the main path flow direction (co-current); and vice versa for minimum values in that the lowest amounts of air travel against the direction of the main path flow (countercurrent).

Conversely, station four shows that the slip ratio varies with lower magnitudes, with no negative values, and ultimately approaches unity towards the end of the simulation. This particular behavior suggests that air bubbles are continuously flowing co-currently despite the amount of air.

The void fraction, as well as the slip ratio behavior seen in simulation scenario one was common for all eight scenarios, and the results are summarized in Appendix D.2.

Void Fraction Results The simulation flow regime at station three (for all scenarios) varied between horizontally stratified and bubbly flow. Even though not immediately apparent, the continuous combination between these two regimes is a product of slug flow, and matches the experimental flow regime observation previously described in Section 3.1.2.4. However, it is important to mention that the extreme void fraction oscillating behavior for simulation scenarios five through seven nearly disappeared between 35 and approximately 75 seconds of the simulation. This particular behavior, nearly disappearing oscillation, can be seen in Figure D.13 through Figure D.15, which was caused by a steadier mass flow rate through the VRP as explained in Section 3.4.1. A steady two-component mass flow rate implies a steady amount of air and water flow rates, which ultimately results in a steady void fraction. Because the check valve in the VRP remains open during this time, then a steady amount of void fraction is reflected in stations two and three. Station four is also affected by a steady void fraction behavior meaning that a constant amount of air is passing through without being recirculated and ultimately exits the VRS by returning to the tank. Though, it is important to note that the magnitudes are much lower when compared to stations two and three.

One important distinction seen in simulation scenarios four and eight, which correspond to a Froude number of 1.6, is that air recirculation ceases towards the end of the simulation, as was described in the mass flow rate behavior. Figure 3.23 shows this particular behavior for simulation scenario eight (6x6x4-inch, $Fr = 1.6$). The main reason why air recirculation ceases is probably caused by a higher Froude number that ultimately allows the air to exit the VRS at a higher rate through station four, and as a consequence travels back to the tank. At high Froude numbers, there is less time for the air, coming from station three, to rise through the vertical VRP. In other words, the air bubble at high Froude numbers is traveling so fast through station three that it basically ignores the effect of the upwards oriented lower tee, which is supposed to remove the air by recirculating it throughout the system. From this reasoning, it is recommended to avoid high Froude numbers to prevent large and continuous air bubbles from entering station four, assuming the same VRS configuration is used in practice. It is possible that other VRS configurations might have a more efficient method in recirculating the air at high Froude numbers, and it is strongly suggested to perform further analysis by trying different pipe diameters and/or other parts that do not require moving parts, such as the check valve.

Figure 3.23. Void fraction behavior for simulation scenario eight: 6x6x4-inch, $Fr = 1.60$.

In short, the VRS numerical results obtained from the simulation for void fraction and slip ratio seem to represent the physical behavior observed during the experiment (Section 3.1.2.), thus supporting the functionality of the VRS model. In addition, it demonstrates the effectiveness of the lower tee configuration in recirculating large amounts of air coming from station three.

3.4.2.2. Lower Elbow Void Fraction

The slip ratio and void fraction behavior at a pipe section after the lower elbow, for simulation scenarios one and eight, are depicted in Figure 3.24 and Figure 3.25, respectively. Pipe components 320-23 and 420-18 refer to the pipe section after the

lower elbow for pipe configurations 4x4x3-inch and 6x6x4-inch, respectively. Solid and dashed lines are used to measure slip ratio and void fraction, respectively.

Figure 3.24. Slip ratio and void fraction behavior at pipe section after lower elbow, for simulation scenario one: 4x4x3-inch, $Fr = 0.81$.

Figure 3.24 shows a similar behavior as Figure 3.22 in that the slip ratio approaches zero in an oscillatory motion towards the end of the simulation, while the void fraction continues to oscillate between the approximate values of 0.2 and 0.5. This behavior, while in part triggered by the check valve open/close operation, could also be due to the relatively low Froude numbers since there is not enough flow to carry the air in a continuous manner. In addition, the change in direction at the lower elbow contributes to the formation of large voids due to a localized lower pressure. This in turn, creates a discontinuity in the flow causing a slug flow behavior. According to the numerical results, the simulated Froude numbers of 0.80, 1.0 and 1.3, indicated that the slip ratio

and void fraction behaved similarly. In contrast, only the highest simulated Froude number of 1.6, for scenarios four and eight, indicated that air recirculation ceased towards the end of the simulation as seen in Figure 3.25. This particular behavior indicates that the majority of the air has exited the VRS through station four and has returned to the tank. These two graphs are in good agreement with the observations done in the experiment and are intended to support the bubble behavior seen at station three for all simulation scenarios.

Figure 3.25. Slip ratio and void fraction behavior at pipe section after lower elbow, for simulation scenario eight: 6x6x4-inch, $Fr = 1.6$.

3.4.3. Simulation and Experimental Void Fraction Validation

Now that the VRS model has been verified with respect to experimental observations and plausible explanations for the different flow behaviors seen in the pipe sections of interest, the validation between simulation and experimental void fraction results can be analyzed. More specifically, time-averaged void fraction values will be compared in order to validate the VRS model built in RELAP5. Since the void fraction experimental results were averaged for a period of approximately 120 seconds for each scenario, which represents the time at which station four reached a void fraction less than one percent, then it makes sense to average the void fraction numerical results for the period of time that satisfies the void fraction condition at station four. Figure 3.26 shows the void fraction validation between experimental and numerical (model) results, at stations one through four, for simulation scenario one (4x4x3-inch, $Fr = 0.81$).

Figure 3.26. Void fraction validation of the VRS model for simulation scenario one: 4x4x3-inch, $Fr = 0.81$.

The bars shown in this graph actually represent uncertainty ranges, rather than error bars, since insufficient experimental data was available for a thorough statistical analysis. Solid and dashed bars represent experimental and model uncertainty ranges, respectively. The experimental uncertainty associated with the void fraction at each station was approximately ± 0.5 inches, since this value was much larger than the other parameters (length and pipe diameter uncertainty) used for general uncertainty propagation. This specific value was determined by visually inspecting the length variation (in inches) of the void fraction. Figure 3.27 shows a schematic of a pipe partially filled with water, along with the variables used to calculate the void fraction. The air phase is occupying the top portion of the inner pipe diameter, while the water phase is occupying the bottom

portion. The variables y , r and θ measure the air level from the top of the pipe, pipe radius and water contact angle, respectively.

Figure 3.27. Schematic of a pipe partially filled with water.

The cross-sectional area occupied by the air phase can be calculated using the following expression:

$$A_g = \frac{D^2}{8} [\theta - \sin \theta] \quad (3.10)$$

where D is twice the radius r . The water contact angle, θ , can be obtained geometrically using:

$$\theta = 2 \cos^{-1} \left(1 - \frac{2y}{D} \right) \quad (3.11)$$

The void fraction is finally calculated using equation 2.3. The uncertainty of ± 0.5 inches previously mentioned was translated into void fraction by observing the total variation in y and then using equations 2.3, 3.2 and 3.3. This uncertainty range corresponds to $\pm 7.2\%$

and $\pm 3.9\%$ void fraction for four inch and six inch pipe diameters, respectively. As a result, all void fractions calculated for the four inch pipe had greater uncertainty values.

For this particular scenario validation, the numerical results over predicted the experimental results at stations one and four, and under predicted the experimental results at stations two and three. Nonetheless, the uncertainty ranges of both experimental and model results at each station overlap with each other, meaning that any of the values could fall in this range at any particular time. Uncertainty overlapping not only proves that the model resembles realistic behavior, but also validates the VRS model built in RELAP5.

In regards to the remaining simulation scenarios, the void fraction validation was achieved for the majority of Froude numbers and stations of interest. A summary of the validation plots can be seen in Appendix E – VRS Simulation and Experimental Void Fraction Validation for further reference. However, it is important to note that the validation at station three, which is of highest significance, was not achieved in the following three scenarios: four, seven and eight. It is believed that the apparent under-prediction of the numerical results for these scenarios was not the cause for a non-numerical validation. On the contrary, it is believed the all void fraction values obtained from the experiment were too conservative and thus over-predicted the actual value.

Chapter 4. CONCLUSIONS AND RECOMMENDATIONS

4.1. Conclusions

In conclusion, the objectives of this thesis were accomplished by (1) simulating a Void Recirculation System model using RELAP5 and investigating the behavior of two-component flow by means of analyzing mass flow rates, void fraction and slip ratios; and (2) successfully validating its results with respect to experimental results and observations.

The Void Recirculation System model, simulated in RELAP5, was successfully validated against experimental results using the void fraction parameter. A total of eight simulation scenarios were analyzed using two different pipe configurations (4x4x3-inch and 6x6x4-inch), and four Froude numbers (0.80, 1.0, 1.3 and 1.6). The void fraction numerical results obtained from RELAP5 were in good agreement with experimental results and represent the physical behavior seen during the Void Recirculation System experiment.

The numerical results confirmed that air recirculation is more effective at Froude numbers of 0.80, 1.0 and 1.3, which resemble experimental observations. At these Froude numbers, recirculation occurs indefinitely, or for a long period of time, since air does not travel fast enough to exit the Void Recirculation System. Conversely, the numerical results showed that air recirculation occurs for a short period of time, and ceases towards the end of the simulation at the highest Froude number simulated of 1.6. For this reason, high Froude numbers, and thus high flow rates, should be avoided if air is to be recirculated more effectively. The void fraction and mass flow rate oscillating

motion observed in the numerical results were associated with both the check valve open/close operation, as well as with the flow discontinuities produced by the lower elbow and lower tee.

The air reduction effectiveness due to the use of the 4x4x3-inch and 6x6x4-inch pipe configurations was approximately 90% for all simulation scenarios. Even though this Void Recirculation System model was analyzed on the discharge side of the pump, it can be potentially used as a computational tool to solve the problem of large voids in suction piping at nuclear power plants, or wherever this problem is encountered.

4.2. Recommendations

In the attempt of validating the Void Recirculation System model, the lack of accurate experimental results along with a poor statistical analysis did not contribute in a more detailed explanation of the numerical results. For this, it is recommended to design a better experiment with higher precision instruments that entail all parameters of interest. Furthermore, the experiment should be performed under suction conditions to fully grasp the air behavior due to the Void Recirculation System.

The question of scalability for two-component flow in a Void Recirculation System was raised when the pipe configurations 4x4x3-inch and 6x6x4-inch were compared. Even though simulation initial conditions were the same for both pipe configurations, including the same initial void fraction, the air had a tendency to behave differently. A study of the Weber number influence for wavy horizontally stratified flow

at elbows and tees is recommended to better understand the scalability of the Void Recirculation System for different pipe diameters.

Finally, the modeling of other pipe configurations (using the VRS model) that recirculate air is strongly suggested, since it could help to decide what diameters are appropriate for each application. In addition, it is recommended to model other VRS ideas that could improve air recirculation by not having to use moving parts, such as a check valve. These recommended computational efforts can expand the validity of the VRS model, lower experiment expenses and could help identify if the VRS solution is suitable for a particular application.

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Appendix A – VRS Piping Drawings

Figure A.1. 4x4x3-inch VRS Pipe Configuration Drawing.

Figure A.2. 6x6x4" VRS Pipe Configuration Drawing.

Appendix B – VRS Pipe Data

Comp Name	SubComp	Length (ft)	Dia (in)	Flow Area (ft^2)	K	Vol Angle (deg)	Centroid Elev (ft)	Centroid (PSIA)
TMDPVOL 200	200					0		
TMDJUN205	205		6.065	0.2006		0		
Pipe 210	210-1	1.000	6.065	0.2006	0	0	3.768	14.584
	210-2	1.000	6.065	0.2006	0	0	3.768	14.584
	210-3	1.000	6.065	0.2006	0	0	3.768	14.584
	210-4	1.000	6.065	0.2006	0	0	3.768	14.584
90 Elbow	210-5	1.000	6.065	0.2006	0.45	-90	3.268	14.800
	210-6	1.000	6.065	0.2006	0	-90	2.268	15.233
	210-7	1.000	6.065	0.2006	0	-90	1.268	15.666
	210-8	1.000	6.065	0.2006	0	-90	0.268	16.099
90 Elbow	210-9	1.000	6.065	0.2006	0.45	0	0.268	16.099
	210-10	1.000	6.065	0.2006	0	0	0.268	16.099
	210-11	1.000	6.065	0.2006	0	0	0.268	16.099
	210-12	1.000	6.065	0.2006	0	0	0.268	16.099
	210-13	1.000	6.065	0.2006	0	0	0.268	16.099
	210-14	1.000	6.065	0.2006	0	0	0.268	16.099
	210-15	1.000	6.065	0.2006	0	0	0.268	16.099
	210-16	1.000	6.065	0.2006	0	0	0.268	16.099
	210-17	1.000	6.065	0.2006	0	0	0.268	16.099
	210-18	1.000	6.065	0.2006	0	0	0.268	16.099
	210-19	1.000	6.065	0.2006	0	0	0.268	16.099
	210-20	1.000	6.065	0.2006	0	0	0.268	16.099
	210-21	1.000	6.065	0.2006	0	0	0.268	16.099
	210-22	1.000	6.065	0.2006	0	0	0.268	16.099
	210-23	1.000	6.065	0.2006	0	0	0.268	16.099
	210-24	1.000	6.065	0.2006	0	0	0.268	16.099
	210-25	1.000	6.065	0.2006	0	0	0.268	16.099
	210-26	0.506	6.065	0.2006	0	0	0.268	16.099
	210-27	0.506	6.065	0.2006	0	0	0.268	16.099
6" x 4"	210-28	0.500	4.026	0.0884	0.931	0	0.268	16.099
	210-29	0.500	4.026	0.0884	0	0	0.268	16.099
	210-30	0.500	4.026	0.0884	0	0	0.268	16.099
	210-31	0.500	4.026	0.0884	0	0	0.268	16.099
	210-32	0.500	4.026	0.0884	0	0	0.268	16.099
	210-33	0.500	4.026	0.0884	0	0	0.268	16.099
4" x 6"	210-34	0.506	6.065	0.2006	0.309	0	0.268	16.099
	210-35	0.506	6.065	0.2006	0	0	0.268	16.099
	210-36	0.506	6.065	0.2006	0	0	0.268	16.099
	210-37	0.506	6.065	0.2006	0	0	0.268	16.099
	210-38	0.506	6.065	0.2006	0	0	0.268	16.099
	210-39	0.506	6.065	0.2006	0	0	0.268	16.099
	210-40	0.506	6.065	0.2006	0	0	0.268	16.099
	210-41	0.506	6.065	0.2006	0	0	0.268	16.099

	210-42	0.506	6.065	0.2006	0	0	0.268	16.099
90 Elbow	210-43	0.506	6.065	0.2006	0.45	90	0.774	15.880
	210-44	0.506	6.065	0.2006	0	90	1.280	15.661
	210-45	0.506	6.065	0.2006	0	90	1.786	15.442
	210-46	0.506	6.065	0.2006	0	90	2.292	15.223
	210-47	0.506	6.065	0.2006	0	90	2.798	15.004
	210-48	0.506	6.065	0.2006	0	90	3.304	14.785
	210-49	0.506	6.065	0.2006	0	90	3.810	14.565
	210-50	0.506	6.065	0.2006	0	90	4.316	14.346
	210-51	0.506	6.065	0.2006	0	90	4.822	14.127
	210-52	0.506	6.065	0.2006	0	90	5.328	13.908
	210-53	0.506	6.065	0.2006	0	90	5.834	13.689
	210-54	0.506	6.065	0.2006	0	90	6.340	13.470
	210-55	0.506	6.065	0.2006	0	90	6.846	13.251
	210-56	0.506	6.065	0.2006	0	90	7.352	13.032
	210-57	0.506	6.065	0.2006	0	90	7.858	12.813
	210-58	0.506	6.065	0.2006	0	90	8.364	12.594
90 Elbow	210-59	0.506	6.065	0.2006	0.45	0	8.364	12.594
	210-60	0.506	6.065	0.2006	0	0	8.364	12.594
	210-61	0.506	6.065	0.2006	0	0	8.364	12.594
	210-62	0.506	6.065	0.2006	0	0	8.364	12.594
	210-63	0.506	6.065	0.2006	0	0	8.364	12.594
Branch 220	220-1	1.000	6.065	0.2006		0	8.000	12.594
Pipe 230	230-1	0.506	6.065	0.2006	0	0	8.000	12.594
	230-2	0.506	6.065	0.2006	0	0	8.000	12.594
	230-3	0.506	6.065	0.2006	0	0	8.000	12.594
	230-4	0.506	6.065	0.2006	0	0	8.000	12.594
	230-5	0.643	6.065	0.2006	0	0	8.000	12.594
Pipe 500	500-1	0.506	6.065	0.2006	0	0	8.000	12.594
	500-2	0.506	6.065	0.2006	0	0	8.000	12.594
	500-3	0.506	6.065	0.2006	0	0	8.000	12.594
	500-4	0.506	6.065	0.2006	0	0	8.000	12.594
	500-5	0.506	6.065	0.2006	0	0	8.000	12.594
6" x 8"	500-6	0.700	7.981	0.3474	0.191	0	8.000	12.594
	500-7	0.700	7.981	0.3474	0	0	8.000	12.594
	500-8	0.700	7.981	0.3474	0	0	8.000	12.594
	500-9	0.700	7.981	0.3474	0	0	8.000	12.594
	500-10	0.700	7.981	0.3474	0	0	8.000	12.594
	500-11	0.700	7.981	0.3474	0	0	8.000	12.594
	500-12	0.700	7.981	0.3474	0	0	8.000	12.594
	500-13	0.700	7.981	0.3474	0	0	8.000	12.594
	500-14	0.900	7.981	0.3474	0	0	8.000	12.594
Branch 240	240-1	1.000	6.065	0.2006	0	0	8.000	12.594
Pipe 400	400-1	0.506	6.065	0.2006	0	0	8.000	12.594
	400-2	0.506	6.065	0.2006	0	0	8.000	12.594
	400-3	0.506	6.065	0.2006	0	0	8.000	12.594
	400-4	0.506	6.065	0.2006	0	0	8.000	12.594
	400-5	0.506	6.065	0.2006	0	0	8.000	12.594

	400-6	0.506	6.065	0.2006	0	0	8.000	12.594
	400-7	0.506	6.065	0.2006	0	0	8.000	12.594
	400-8	0.506	6.065	0.2006	0	0	8.000	12.594
	400-9	0.535	6.065	0.2006	0	0	8.000	12.594
Pipe 401	401-1	0.506	6.065	0.2006	0	0	8.000	12.594
	401-2	0.506	6.065	0.2006	0	0	8.000	12.594
	401-3	0.506	6.065	0.2006	0	0	8.000	12.594
	401-4	0.506	6.065	0.2006	0	0	8.000	12.594
	401-5	0.506	6.065	0.2006	0	0	8.000	12.594
	401-6	0.506	6.065	0.2006	0	0	8.000	12.594
	401-7	0.506	6.065	0.2006	0	0	8.000	12.594
	401-8	0.506	6.065	0.2006	0	0	8.000	12.594
	401-9	0.535	6.065	0.2006	0	0	8.000	12.594
TMDPVOL 402	402					0		60.000
TMDJUN 403	403		6.065	0.2006		0		
SNGLVOL 404	404	5.000	0.364	0.0007	0	0	8.000	12.594
CHCKVLV 405	405		0.364	0.0007	3	0	8.000	12.594
SNGLVOL 406	406	5.000	0.364	0.0007	0	0	8.000	12.594
BRANCH 407	407	1.000	6.065	0.2006	0	0	8.000	12.594
Branch 410	410-1	1.000	6.065	0.2006	0	0	8.000	12.594
Pipe 420	420-1	0.556	6.065	0.2006	0	0	8.000	12.594
	420-2	0.556	6.065	0.2006	0	0	8.000	12.594
	420-3	0.556	6.065	0.2006	0	0	8.000	12.594
	420-4	0.556	6.065	0.2006	0	0	8.000	12.594
	420-5	0.556	6.065	0.2006	0	0	8.000	12.594
	420-6	0.506	6.065	0.2006	0.45	-45	7.821	12.671
45 elbow	420-7	0.743	6.065	0.2006	0	-90	7.629	12.755
	420-8	0.743	6.065	0.2006	0	-90	6.886	13.076
	420-9	0.743	6.065	0.2006	0	-90	6.144	13.398
	420-10	0.743	6.065	0.2006	0	-90	5.401	13.719
	420-11	0.743	6.065	0.2006	0	-90	4.658	14.041
	420-12	0.743	6.065	0.2006	0	-90	3.916	14.362
	420-13	0.743	6.065	0.2006	0	-90	3.173	14.684
	420-14	0.743	6.065	0.2006	0	-90	2.431	15.005
	420-15	0.743	6.065	0.2006	0	-90	1.688	15.327
	420-16	1.184	6.065	0.2006	0	-90	0.504	15.839
45 elbow	420-17	0.506	6.065	0.2006	0.45	-45	0.072	16.026
	420-18	0.556	6.065	0.2006	0	0	-0.206	16.147
	420-19	0.556	6.065	0.2006	0	0	-0.206	16.147
	420-20	0.556	6.065	0.2006	0	0	-0.206	16.147
	420-21	0.556	6.065	0.2006	0	0	-0.206	16.147
	420-22	0.556	6.065	0.2006	0	0	-0.206	16.147
Branch 430	430-1	1.000	6.065	0.2006		0	-0.206	16.147
Pipe 800	800-1	0.326	4.026	0.0513	0	90	-0.043	16.076
	800-2	0.326	4.026	0.0513	0	90	0.282	15.935
	800-3	0.326	4.026	0.0513	0	90	0.608	15.794
	800-4	0.326	4.026	0.0513	0	90	0.934	15.653

4 x 2 reducer	800-5	0.326	2.067	0.0233	0.992	90	1.260	15.512
	800-6	0.326	2.067	0.0233	0	90	1.585	15.371
	800-7	0.326	2.067	0.0233	0	90	1.911	15.230
	800-8	0.326	2.067	0.0233	0	90	2.237	15.089
	800-9	0.326	2.067	0.0233	0	90	2.563	14.948
	800-10	0.326	2.067	0.0233	0	90	2.888	14.807
	800-11	0.326	2.067	0.0233	0	90	3.214	14.666
	800-12	0.326	2.067	0.0233	0	90	3.540	14.525
	800-13	0.326	2.067	0.0233	0	90	3.866	14.384
	800-14	0.326	2.067	0.0233	0	90	4.192	14.243
	800-15	0.326	2.067	0.0233	0	90	4.517	14.102
	800-16	0.326	2.067	0.0233	0	90	4.843	13.961
	800-17	0.326	2.067	0.0233	0	90	5.169	13.820
	800-18	0.326	2.067	0.0233	0	90	5.495	13.679
	800-19	0.326	2.067	0.0233	0	90	5.820	13.537
	800-20	0.326	2.067	0.0233	0	90	6.146	13.396
	800-21	0.326	2.067	0.0233	0	90	6.472	13.255
	800-22	0.326	2.067	0.0233	0	90	6.798	13.114
Chkvalve 810	810-1	1.000	2.067	0.0233	0.95	0	6.798	13.114
Pipe 820	820-1	0.200	2.067	0.0233	0	90	6.898	13.071
	820-2	0.200	2.067	0.0233	0	90	7.098	12.984
	820-3	0.200	2.067	0.0233	0	90	7.298	12.898
	820-4	0.311	2.067	0.0233	0	90	7.453	12.831
Pipe 440	440-1	0.506	6.065	0.2006	0	0	-0.206	16.147
	440-2	0.506	6.065	0.2006	0	0	-0.206	16.147
	440-3	0.506	6.065	0.2006	0	0	-0.206	16.147
	440-4	0.506	6.065	0.2006	0	0	-0.206	16.147
	440-5	0.506	6.065	0.2006	0	0	-0.206	16.147
	440-6	0.506	6.065	0.2006	0	0	-0.206	16.147
	440-7	0.506	6.065	0.2006	0	0	-0.206	16.147
	440-8	0.506	6.065	0.2006	0	0	-0.206	16.147
	440-9	0.506	6.065	0.2006	0	0	-0.206	16.147
	440-10	0.506	6.065	0.2006	0	0	-0.206	16.147
Valve 450	450-1	0.000	6.065	0.2006	0.019		-0.206	16.147
Pipe 460	460-1	0.890	6.065	0.2006	0	0	-0.206	16.147
	460-2	0.890	6.065	0.2006	0	0	-0.206	16.147
	460-3	0.890	6.065	0.2006	0	0	-0.206	16.147
	460-4	0.890	6.065	0.2006	0	0	-0.206	16.147
Branch 630	630-1	1.000	6.065	0.2006	0	0	-0.206	16.147
Pipe 640	640-1	0.506	6.065	0.2006	0	0	-0.206	16.147
	640-2	0.506	6.065	0.2006	0	0	-0.206	16.147
	640-3	0.506	6.065	0.2006	0	0	-0.206	16.147
	640-4	0.506	6.065	0.2006	0	0	-0.206	16.147
	640-5	0.506	6.065	0.2006	0	0	-0.206	16.147
90 Elbow	640-6	0.506	6.065	0.2006	0.45	0	-0.206	16.147
	640-7	0.506	6.065	0.2006	0	0	-0.206	16.147
	640-8	0.506	6.065	0.2006	0	0	-0.206	16.147

	640-9	0.506	6.065	0.2006	0	0	-0.206	16.147
	640-10	0.506	6.065	0.2006	0	0	-0.206	16.147
	640-11	0.506	6.065	0.2006	0	0	-0.206	16.147
	640-12	0.506	6.065	0.2006	0	0	-0.206	16.147
Pipe 620	620-1	0.506	6.065	0.2006	0	0	-0.206	16.147
	620-2	0.506	6.065	0.2006	0	0	-0.206	16.147
	620-3	0.506	6.065	0.2006	0	0	-0.206	16.147
	620-4	0.574	6.065	0.2006	0	0	-0.206	16.147
	620-5	0.574	6.065	0.2006	0	0	-0.206	16.147
Branch 610	610-1	1.000	6.065	0.2006	0	0	-0.206	16.147
Pipe 600	600-1	0.506	6.065	0.2006	0	0	-0.206	16.147
	600-2	0.506	6.065	0.2006	0	0	-0.206	16.147
	600-3	0.506	6.065	0.2006	0	0	-0.206	16.147
	600-4	0.506	6.065	0.2006	0	0	-0.206	16.147
	600-5	0.506	6.065	0.2006	0	0	-0.206	16.147
	600-6	0.506	6.065	0.2006	0	0	-0.206	16.147
	600-7	0.506	6.065	0.2006	0	0	-0.206	16.147
	600-8	0.506	6.065	0.2006	0	0	-0.206	16.147
	600-9	0.506	6.065	0.2006	0	0	-0.206	16.147
	600-10	0.506	6.065	0.2006	0	0	-0.206	16.147
	600-11	0.506	6.065	0.2006	0	0	-0.206	16.147
	600-12	0.506	6.065	0.2006	0	0	-0.206	16.147
	600-13	0.506	6.065	0.2006	0	0	-0.206	16.147
	600-14	0.506	6.065	0.2006	0	0	-0.206	16.147
	600-15	0.506	6.065	0.2006	0	0	-0.206	16.147
	600-16	0.506	6.065	0.2006	0	0	-0.206	16.147
	600-17	0.506	6.065	0.2006	0	0	-0.206	16.147
	600-18	0.506	6.065	0.2006	0	0	-0.206	16.147
	600-19	0.506	6.065	0.2006	0	0	-0.206	16.147
	600-20	0.506	6.065	0.2006	0	0	-0.206	16.147
	600-21	0.506	6.065	0.2006	0	0	-0.206	16.147
	600-22	0.506	6.065	0.2006	0	0	-0.206	16.147
	600-23	0.506	6.065	0.2006	0	0	-0.206	16.147
	600-24	0.506	6.065	0.2006	0	0	-0.206	16.147
	600-25	0.506	6.065	0.2006	0	0	-0.206	16.147
	600-26	0.506	6.065	0.2006	0	0	-0.206	16.147
	600-27	0.506	6.065	0.2006	0	0	-0.206	16.147
	600-28	0.506	6.065	0.2006	0	0	-0.206	16.147
90 Elbow	600-29	0.506	6.065	0.2006	0.45	90	0.300	15.928
	600-30	0.506	6.065	0.2006	0	90	0.806	15.709
	600-31	0.506	6.065	0.2006	0	90	1.312	15.490
	600-32	0.506	6.065	0.2006	0	90	1.818	15.270
	600-33	0.506	6.065	0.2006	0	90	2.324	15.051
	600-34	0.506	6.065	0.2006	0	90	2.830	14.832
	600-35	0.506	6.065	0.2006	0	90	3.336	14.613
	600-36	0.506	6.065	0.2006	0	90	3.842	14.394
	600-37	0.506	6.065	0.2006	0	90	4.348	14.175
	600-38	0.506	6.065	0.2006	0	90	4.854	13.956

90 Elbow	600-39	0.506	6.065	0.2006	0.45	0	4.854	13.956
	600-40	0.506	6.065	0.2006	0	0	4.854	13.956
	600-41	0.506	6.065	0.2006	0	0	4.854	13.956
	600-42	0.506	6.065	0.2006	0	0	4.854	13.956
	600-43	0.506	6.065	0.2006	0	0	4.854	13.956
	600-44	0.506	6.065	0.2006	0	0	4.854	13.956
	600-45	0.506	6.065	0.2006	0	0	4.854	13.956
	600-46	0.506	6.065	0.2006	0	0	4.854	13.956
90 Elbow	600-47	0.506	6.065	0.2006	0.45	-90	4.348	14.175
	600-48	0.506	6.065	0.2006	0	-90	3.842	14.394
	600-49	0.506	6.065	0.2006	0	-90	3.336	14.613
	600-50	0.506	6.065	0.2006	0	-90	2.830	14.832
SNGLJUN605	105.000		6.065	0.2006	1.000	0.000		
Pipe 250	250-1	0.506	6.065	0.2006	0	0	8.000	12.594
	250-2	0.506	6.065	0.2006	0	0	8.000	12.594
	250-3	0.506	6.065	0.2006	0	0	8.000	12.594
	250-4	0.506	6.065	0.2006	0	0	8.000	12.594
	250-5	0.506	6.065	0.2006	0	0	8.000	12.594
90 Elbow	250-6	0.506	6.065	0.2006	0.45	0	8.000	12.594
	250-7	0.506	6.065	0.2006	0	0	8.000	12.594
	250-8	0.506	6.065	0.2006	0	0	8.000	12.594
	250-9	0.506	6.065	0.2006	0	0	8.000	12.594
	250-10	0.506	6.065	0.2006	0	0	8.000	12.594
	250-11	0.506	6.065	0.2006	0	0	8.000	12.594
6" x 4"	250-12	0.506	6.065	0.2006	0.931	0	8.000	12.594
	250-13	0.500	4.026	0.0884	0	0	8.000	12.594
	250-14	0.500	4.026	0.0884	0	0	8.000	12.594
	250-15	0.500	4.026	0.0884	0	0	8.000	12.594
	250-16	0.500	4.026	0.0884	0	0	8.000	12.594
	250-17	0.500	4.026	0.0884	0	0	8.000	12.594
	250-18	0.500	4.026	0.0884	0	0	8.000	12.594
Pipe 300	300-1	0.340	4.026	0.0884	0	0	8.000	12.594
	300-2	0.340	4.026	0.0884	0	0	8.000	12.594
	300-3	0.340	4.026	0.0884	0	0	8.000	12.594
	300-4	0.340	4.026	0.0884	0	0	8.000	12.594
	300-5	0.340	4.026	0.0884	0	0	8.000	12.594
	300-6	0.340	4.026	0.0884	0	0	8.000	12.594
	300-7	0.340	4.026	0.0884	0	0	8.000	12.594
	300-8	0.340	4.026	0.0884	0	0	8.000	12.594
	300-9	0.340	4.026	0.0884	0	0	8.000	12.594
	300-10	0.340	4.026	0.0884	0	0	8.000	12.594
Branch 310	310-1	1.000	4.026	0.0884		0	8.000	12.594
Pipe 320	320-1	0.340	4.026	0.0884	0	0	8.000	12.594
	320-2	0.340	4.026	0.0884	0	0	8.000	12.594
	320-3	0.340	4.026	0.0884	0	0	8.000	12.594
	320-4	0.340	4.026	0.0884	0	0	8.000	12.594
	320-5	0.340	4.026	0.0884	0	0	8.000	12.594
	320-6	0.340	4.026	0.0884	0	0	8.000	12.594

	320-7	0.340	4.026	0.0884	0	0	8.000	12.594
	320-8	0.340	4.026	0.0884	0	0	8.000	12.594
	320-9	0.340	4.026	0.0884	0	0	8.000	12.594
	320-10	0.340	4.026	0.0884	0	0	8.000	12.594
45 elbow	320-11	0.340	4.026	0.0884	0.51	-45	7.880	12.646
	320-12	0.657	4.026	0.0884	0	-90	7.672	12.736
	320-13	0.657	4.026	0.0884	0	-90	7.015	13.021
	320-14	0.657	4.026	0.0884	0	-90	6.358	13.305
	320-15	0.657	4.026	0.0884	0	-90	5.701	13.589
	320-16	0.657	4.026	0.0884	0	-90	5.044	13.874
	320-17	0.657	4.026	0.0884	0	-90	4.387	14.158
	320-18	0.657	4.026	0.0884	0	-90	3.730	14.443
	320-19	0.657	4.026	0.0884	0	-90	3.073	14.727
	320-20	0.657	4.026	0.0884	0	-90	2.416	15.012
	320-21	0.657	4.026	0.0884	0	-90	1.759	15.296
45 elbow	320-22	0.340	4.026	0.0884	0.51	-45	1.468	15.422
	320-23	0.340	4.026	0.0884	0	0	1.348	15.474
	320-24	0.340	4.026	0.0884	0	0	1.348	15.474
	320-25	0.340	4.026	0.0884	0	0	1.348	15.474
	320-26	0.340	4.026	0.0884	0	0	1.348	15.474
	320-27	0.340	4.026	0.0884	0	0	1.348	15.474
	320-28	0.340	4.026	0.0884	0	0	1.348	15.474
	320-29	0.340	4.026	0.0884	0	0	1.348	15.474
	320-30	0.340	4.026	0.0884	0	0	1.348	15.474
	320-31	0.340	4.026	0.0884	0	0	1.348	15.474
	320-32	0.340	4.026	0.0884	0	0	1.348	15.474
Branch 330	330-1	1.000	6.065	0.2006		0	1.348	15.474
Pipe 700	700-1	0.260	3.068	0.0513	0	90	1.478	15.417
	700-2	0.260	3.068	0.0513	0	90	1.738	15.305
	700-3	0.260	3.068	0.0513	0	90	1.998	15.192
	700-4	0.260	3.068	0.0513	0	90	2.258	15.080
	700-5	0.260	3.068	0.0513	0	90	2.518	14.967
	700-6	0.260	3.068	0.0513	0	90	2.778	14.855
3 x 2 reducer	700-7	0.263	2.067	0.0233	0.992	90	3.041	14.741
	700-8	0.263	2.067	0.0233	0	90	3.303	14.627
	700-9	0.263	2.067	0.0233	0	90	3.566	14.514
	700-10	0.263	2.067	0.0233	0	90	3.828	14.400
	700-11	0.263	2.067	0.0233	0	90	4.091	14.286
	700-12	0.263	2.067	0.0233	0	90	4.353	14.173
	700-13	0.263	2.067	0.0233	0	90	4.616	14.059
	700-14	0.263	2.067	0.0233	0	90	4.878	13.945
	700-15	0.263	2.067	0.0233	0	90	5.141	13.832
	700-16	0.263	2.067	0.0233	0	90	5.403	13.718
	700-17	0.263	2.067	0.0233	0	90	5.666	13.605
	700-18	0.263	2.067	0.0233	0	90	5.928	13.491
	700-19	0.263	2.067	0.0233	0	90	6.191	13.377
	700-20	0.263	2.067	0.0233	0	90	6.453	13.264
	700-21	0.263	2.067	0.0233	0	90	6.716	13.150

	700-22	0.263	2.067	0.0233	0	90	6.978	13.036
Chkvalve 710	710-1	1.000	2.067	0.0233	0.95	0	6.978	13.036
Pipe 720	720-1	0.200	2.067	0.0233	0	90	7.078	12.993
	720-2	0.200	2.067	0.0233	0	90	7.278	12.906
	720-3	0.200	2.067	0.0233	0	90	7.478	12.820
	720-4	0.311	2.067	0.0233	0	90	7.634	12.752
Pipe 340	340-1	0.350	4.026	0.0884	0	0	1.348	15.474
	340-2	0.350	4.026	0.0884	0	0	1.348	15.474
	340-3	0.350	4.026	0.0884	0	0	1.348	15.474
	340-4	0.350	4.026	0.0884	0	0	1.348	15.474
	340-5	0.350	4.026	0.0884	0	0	1.348	15.474
	340-6	0.350	4.026	0.0884	0	0	1.348	15.474
	340-7	0.350	4.026	0.0884	0	0	1.348	15.474
	340-8	0.350	4.026	0.0884	0	0	1.348	15.474
	340-9	0.350	4.026	0.0884	0	0	1.348	15.474
	340-10	0.350	4.026	0.0884	0	0	1.348	15.474
	340-11	0.350	4.026	0.0884	0	0	1.348	15.474
	340-12	0.350	4.026	0.0884	0	0	1.348	15.474
	340-13	0.350	4.026	0.0884	0	0	1.348	15.474
	340-14	0.350	4.026	0.0884	0	0	1.348	15.474
Valve 350	350-1	0.000	4.026	0.0884	0.019		1.348	15.474
Pipe 360	360-1	0.506	4.026	0.0884	0	0	0.000	16.147
	360-2	0.506	4.026	0.0884	0	0	0.000	16.147
	360-3	0.506	4.026	0.0884	0	0	0.000	16.147
6" x 4"	360-4	0.506	4.026	0.0884	0.931	0	0.000	16.147
	360-5	0.900	6.065	0.2006	0	0	0.000	16.147
	360-6	0.900	6.065	0.2006	0	0	0.000	16.147
	360-7	0.900	6.065	0.2006		0	0.000	16.147

Appendix C – VRS RELAP5 Code

=vrs_443_1

* This case evaluates transient two-phase flow in the 4 inch test loop

*

* Fr = 0.80, 4x4x3 Pipe configuration, Initial Void Fraction ~ 8%

*

*

*cardno	Problem Type	Problem Option
0000100	new	transnt

*

*-----

*

*cardno	
0000101	run

*

*-----

*

*cardno	Input Units	Output Units
0000102	british	british

*

*cardno	NonCondensable Gas Type
0000110	air

*

*-----

*Time Step Control Cards

*

*cardno	time end	min time step	max time step	ssdtt	min	major	rstrt
0000201	5.0	1.0e-6	0.01	0003	100	1000	100000000
0000202	10.0	1.0e-6	1.0e-2	0003	100	1000	100000000
0000203	20.0	1.0e-6	1.0e-2	0003	100	1000	100000000
0000204	30.0	1.0e-6	1.0e-3	0003	1000	10000	100000000
0000205	40.0	1.0e-6	1.0e-3	0003	1000	10000	100000000
0000206	60.0	1.0e-6	1.0e-3	0003	1000	10000	100000000
0000207	150.0	1.0e-6	1.0e-3	0003	1000	10000	100000000

*

*-----

*

*Minor Edit Variables

*

*cardno	Variable Code	Parameter
0000301	dt	0
0000302	cputime	0
0000303	dcrnt	0
0000304	emass	0
0000305	p	300050000

0000306	p	320080000
0000307	p	320280000
0000308	p	340030000
0000309	mflowj	300050000
0000310	mflowj	320080000
0000311	mflowj	340030000
0000312	mflowj	330030000
0000313	voidg	300050000
0000314	voidg	320080000
0000315	voidg	320280000
0000316	voidg	340030000
0000317	voidg	700220000
0000318	voidg	320230000
0000319	florej	300050000
0000320	florej	320080000
0000321	florej	320190000
0000322	florej	320280000
0000323	florej	340030000
0000324	florej	700220000
0000325	velf	320080000
0000326	velg	320080000
0000327	velf	320190000
0000328	velg	320190000
0000329	velf	320230000
0000330	velg	320230000
0000331	velf	320280000
0000332	velg	320280000
0000333	velf	340030000
0000334	velg	340030000

*

*-----

* Trip Data

*-----

*

* 501 & 502 trip on pump flow TDPJUN 105 and TDPJUN 105

*cardno VAR1 NUM1 COND VAR2 NUM2 CONT LATCH TIMEOF

501 time 0 gt null 0 0.0 1 -1.0 *ON TIME

502 time 0 lt null 0 0.0 n -1.0 *ON TIME

*

*

*-----

* Time Dependent Volume 200 establishes pressure and enthalpy for pump discharge fluid

*-----

*

*crdno name type

```

2000000    pump200    tmdpvol
*
*cardno  area    length    volume
2000101  0.0     10.0     1000.00
*
*cardno  azim angle  incl. Angle  deltaz
2000102  0.0       0.0       0.0
*
*cardno  roughness      hyddia    pvbfe
2000103  0.0             0.0      00010
*
*cardno  ebt      trip      search var*
2000200  003
*
*      time          press          temp
2000201  0.00          65.0          70.0
2000202  10.0          65.0          70.0
2000203  1.0e6          65.0          70.0
*
*-----
* Time dependent junction 205 establishes pump discharge mass flow rate to pipe 210
* TDJUN 205 discharge mass flow rate vs time must equal TDJUN 115 suction flow
*-----
*crdno    name      type
2050000  jun205      tmdpjun
*
*cardno  from      to          area
2050101  2000000000    2100000000    0.2006
*
*cardno  vel/flow  trip  search variable
2050200  1            0
*
*cardno  time      mdot-1      mdot-v    mdot-if
2050201  0.0      0.0        0.0      0.0
2050202  5.0      14.540     0.0      0.0
2050203  10.0     14.540     0.0      0.0
2050204  1.0e6    14.540     0.0      0.0
*
*-----
* Pipe-210 6" pump discharge line to BRANCH 220
*-----
*
*cardno    name      type
2100000  pipe-210    pipe
*
*cardno    # Of Volumes

```

2100001	63		
*			
*cardno	Volume Flow Area		Volume Number
2100101	0.2006		27
2100102	0.0884		33
2100103	0.2006		63
*			
*cardno	Junction Flow Area		Junction Number
2100201	0.2006		26
2100202	0.0884		32
2100203	0.2006		62
*			
*cardno	volume lengths		Volume Number
2100301	1.0		25
2100302	0.506		27
2100303	0.5		33
2100304	0.506		63
*			
*cardno	Volume		Volume Number
2100401	0.0		63
*			
*cardno	Vertical Angle		Volume Number
2100601	0.0		4
2100602	-90.0		8
2100603	0.0		42
2100604	90.0		58
2100605	0.0		63
*			
*cardno	rough	dhyd	Volume Number
2100801	0.00015	0.5054	27
2100802	0.00015	0.3355	33
2100803	0.00015	0.5054	63
*			
*cardno	kfor	krev	Junction Number
2100901	0.0	0.0	3
2100902	0.45	0.45	4
2100903	0.0	0.0	7
2100904	0.45	0.45	8
2100905	0.0	0.0	26
2100906	0.931	0.30	27
2100907	0.0	0.0	32
2100908	0.309	0.931	33
2100909	0.0	0.0	36
2100910	0.0	0.0	37
2100911	0.0	0.0	41
2100912	0.45	0.45	42

2100913	0.0	0.0	57
2100914	0.45	0.45	58
2100915	0.0	0.0	62

*

*cardno	tlpvbfe	Volume Number
2101001	0010000	63

*

*cardno	efvchas	Junction Number
2101101	0001000	62

*

*cardno	ic	press	temp	qual	vol.	
2101201	3	14.584	70.0	0.0	0.0	4
2101202	3	14.800	70.0	0.0	0.0	5
2101203	3	15.233	70.0	0.0	0.0	6
2101204	3	15.666	70.0	0.0	0.0	7
2101205	3	16.099	70.0	0.0	0.0	42
2101206	3	15.880	70.0	0.0	0.0	43
2101207	3	15.661	70.0	0.0	0.0	44
2101208	3	15.442	70.0	0.0	0.0	45
2101209	3	15.223	70.0	0.0	0.0	46
2101210	3	15.004	70.0	0.0	0.0	47
2101211	3	14.785	70.0	0.0	0.0	48
2101212	3	14.565	70.0	0.0	0.0	49
2101213	3	14.346	70.0	0.0	0.0	50
2101214	3	14.127	70.0	0.0	0.0	51
2101215	3	14.908	70.0	0.0	0.0	52
2101216	3	13.689	70.0	0.0	0.0	53
2101217	3	13.470	70.0	0.0	0.0	54
2101218	3	13.251	70.0	0.0	0.0	55
2101219	3	13.032	70.0	0.0	0.0	56
2101220	3	12.813	70.0	0.0	0.0	57
2101221	3	12.594	70.0	0.0	0.0	63

*

*cardno	vel/flow
2101300	1

*

*cardno	liqflow	vaporf	interv	jun
2101301	0.0	0.0	0.0	62

*

*cardno	jct dh	beta	c	m	jun
2101401	0.0	0.0	1.0	1.0	62

*

*

*-----

* Branch 220 6"x6"x6" branch tee connecting pipe-210, pipe-500, and pipe-230

*-----

```

*
*cardno  name          type
2200000  brnch220         branch
*
*cardno  number junctions      initial condition control
2200001  3                      1
*
*cardno  v.flowarea  vlength  v. h-ang v-ang delz rough  dhy  tlpvbf
2200101  0.2006          1.0    0.0 0.0 0.0 0.0 0.00015 0.5054 0010000
*
*cardno  ctl    pressure    temp  qual
2200200  003      12.594      70.0
*
* K thru = 20 ft = 20 x .015 = 0.3
* K branch floss = 60 ft = 60 x .015 = 0.9
*cardno  from          to          area    floss  rloss  efvcahs
2201101  210010000  220000000  0.2006  0.00  0.00  0001100
2202101  220010000  500000000  0.2006  0.30  0.30  0001100
2203101  220010000  230000000  0.2006  0.90  0.90  0001100
*
*
*cardno  flowf      flowg      velj
2201201  0.0             0.0             0.0
2202201  0.0             0.0             0.0
2203201  0.0             0.0             0.0
*
*-----
* Pipe-230 6" line - 6" branch 220 to branch 240
*-----
*
*cardno  name      type
2300000  pipe-230    pipe
*
*cardno  # Of Volumes
2300001  5
*
*cardno  Volume Flow Area      Volume Number
2300101  0.2006                    5
*
*cardno  Junction Flow Area  Junction Number
2300201  0.2006                    4
*
*cardno  volume lengths      Volume Number
2300301  0.506                    4
2300302  0.643                    5
*

```

```

*cardno      Volume      Volume Number
2300401      0.0          5
*
*cardno      Vertical Angle  Volume Number
2300601      0.0          5
*
*cardno      rough      dhyd      Volume Number
2300801      0.00015    0.5054    5
*
*cardno      kfor      krev      Junction Number
2300901      0.0        0.0        4
*
*cardno      tlpvbf      Volume Number
2301001      0010000      5
*
*cardno      efvchas      Junction Number
2301101      0001000      4
*
*cardno      ic   press   temp   qual   W5   W6   vol.
2301201      3    12.594   70.0   0.0    0.0  0.0    5
*
*cardno      vel/flow
2301300      1
*
*cardno      liqflow   vaporf   interv   jun
2301301      0.0     0.0     0.0      4
*
*cardno      jct dh     beta    c    m    jun
2301401      0.0     0.0    1.0   1.0   4
*
*
* -----
* Pipe-500 6" x 8" line  branch 220 to dead end
* -----
*
*cardno      name      type
5000000      pipe-500  pipe
*
*cardno      # Of Volumes
5000001      14
*
*cardno      Volume Flow Area      Volume Number
5000101      0.2006      5
5000102      0.3474      14
*
*cardno      Junction Flow Area      Junction Number

```

5000201	0.2006	4					
5000202	0.3474	13					
*							
*cardno	volume lengths	Volume Number					
5000301	0.506	5					
5000302	0.700	13					
5000303	0.900	14					
*							
*cardno	Volume	Volume Number					
5000401	0.0	14					
*							
*cardno	Vertical Angle	Volume Number					
5000601	0.0	14					
*							
*cardno	rough	dhyd	Volume Number				
5000801	0.00015	0.5054	5				
5000802	0.00015	0.6651	14				
*							
*cardno	kfor	krev	Junction Number				
5000901	0.0	0.0	4				
5000902	0.191	0.472	5				
5000903	0.0	0.0	13				
*							
*cardno	tlpvbfe	Volume Number					
5001001	0010000	14					
*							
*cardno	efvchas	Junction Number					
5001101	0001000	13					
*							
*cardno	ic	press	temp	qual	W5	W6	vol.
5001201	3	12.594	70.0	0.0	0.0	0.0	14
*							
*cardno	vel/flow						
5001300	1						
*							
*cardno	liqflow	vaporf	interv		jun		
5001301	0.0	0.0	0.0		13		
*							
*cardno	jct dh	beta	c	m	jun		
5001401	0.0	0.0	1.0	1.0	13		
*							
*							
*-----							
* Branch 240 6"x6"x6" branch tee connecting pipe-230, pipe-250, and pipe-400							
*-----							

```

*
*cardno  name          type
2400000  brnch240         branch
*
*cardno  number junctions      initial condition control
2400001  3                      1
*
*cardno  v.flowarea  vlength  v. h-ang  v-ang  delz  rough  dhy  tlpvbf
2400101  0.2006        1.0    0.0 0.0  0.0  0.0  0.00015 0.5054 0010000
*
*cardno  ctl      pressure  temp  qual
2400200  003      12.594    70.0
*
* K thru = 20 ft = 20 x .015 = 0.3
* K branch floss = 60 ft = 60 x .015 = 0.9
*cardno  from          to          area    floss  rloss  efvcchs
2401101  230010000    240000000    0.2006  0.00  0.00  0001100
2402101  240010000    250000000    0.2006  0.30  0.30  0001100
2403101  240010000    400000000    0.2006  0.90  0.90  0001100
*
*cardno  flowf      flowg      velj
2401201  0.0      0.0      0.0
2402201  0.0      0.0      0.0
2403201  0.0      0.0      0.0
*
* -----
* Pipe-400 6" test loop line connecting Branch 240 - Dead end
* -----
*
*cardno  name      type
4000000  pipe-400    pipe
*
*cardno  # Of Volumes
4000001  9
*
*cardno  Volume Flow Area      Volume Number
4000101  0.2006                    9
*
*cardno  Junction Flow Area      Junction Number
4000201  0.2006                      8
*
*cardno  volume lengths      Volume Number
4000301  0.506                     8
4000302  0.535                     9
*
*cardno  Volume      Volume Number

```



```

4000401      0.0      9
*
*cardno      Vertical Angle      Volume Number
4000601      0.0      9
*

*cardno      rough      dhyd      Volume Number
4000801      0.00015      0.5054      9
*

*cardno      kfor      krev      Junction Number
4000901      0.0      0.0      8
*

*cardno      tlpvbf      Volume Number
4001001      0010000      9
*

*cardno      efvchas      Junction Number
4001101      0001000      8
*

*cardno      ic      press      temp      qual      W5      W6      vol.
4001201      3      12.594      70.0      0.0      0.0      0.0      9
*

*cardno      vel/flow
4001300      1
*

*cardno      liqflow      vaporf      interv      jun
4001301      0.0      0.0      0.0      8
*

*cardno      jct dh      beta      c      m      jun
4001401      0.0      0.0      1.0      1.0      8
*
*
* -----
*   Pipe-300 4" test loop line connecting Branch 407 to Branch 310
* -----
*

*cardno      name      type
3000000      pipe-300      pipe
*

*cardno      # Of Volumes
3000001      10
*

*cardno      Volume Flow Area      Volume Number
3000101      0.0884      10
*

*cardno      Junction Flow Area      Junction Number
3000201      0.0884      9

```

```

*
*cardno    volume lengths    Volume Number
3000301    0.340             10
*
*cardno    Volume           Volume Number
3000401    0.0              10
*
*cardno    Vertical Angle    Volume Number
3000601    0.0              10
*

*cardno    rough    dhyd    Volume Number
3000801    0.00015    0.3355    10
*
*cardno    kfor    krev    Junction Number
3000901    0.0    0.0    9
*
*cardno    tlpvbf    Volume Number
3001001    0010000    10
*
*cardno    efvchas    Junction Number
3001101    0001000    9
*
*cardno    ic    press    temp    qual    W5    W6    vol.
3001201    3    12.594    70.0    0.0    0.0    0.0    10
*
*cardno    vel/flow
3001300    1
*
*cardno    liqflow    vaporf    interv    jun
3001301    0.0    0.0    0.0    9
*

*cardno    jct dh    beta    c    m    jun
3001401    0.0    0.0    1.0    1.0    9
*
*
* -----
*   Time Dependent Volume 402 establishes pressure for air discharge
* -----
*
*crdno    name    type
4020000    rsrvr402    tmdpvol
*
*cardno    area    length    volume
4020101    10.0    1.0e6    0.0

```

```

*
*cardno  azim angle  incl. Angle  deltaz
4020102  0.0        0.0        0.0
*
*cardno  roughness  hyddia    pvbfe
4020103  0.000005      0.0        00010
*
*cardno  ebt        trip        search var*
4020200  004
*
*      time  press  temp  equil-quality
4020201  0.00  120.0  70.0    0
4020202  5.00  120.0  70.0    0
4020203  10.00 120.0  70.0    0
4020204  20.00 120.0  70.0    0
4020205  1.0e6 120.0  70.0    0
*
*
*-----
*   Time dependent junction 403 establishes air compressor discharge flowrate to
  SNGLVOL 404
*-----
*
*cardno      name      type
4030000      comp403    tmdpjun
*
*cardno      from      to      Junction Area (ft2)
4030101      402010000  404000000      0.00072
*
*cardno  vel/flow  trip  search variable
4030200   1        0
*
*cardno  time      v-l      v-g      v-if
4030201  0.00      0.0      0.0      0.0
4030202  5.00      0.0      0.0      0.0
4030203  17.00     0.0      0.0      0.0
4030204  18.00     0.0      0.5e-3   0.0
4030205  19.00     0.0      1.0e-3   0.0
4030206  20.00     0.0      3.0e-3   0.0
4030207  35.00     0.0      3.0e-3   0.0
4030208  36.00     0.0      2.8e-3   0.0
4030209  37.00     0.0      2.6e-3   0.0
4030210  38.00     0.0      2.4e-3   0.0
4030211  39.00     0.0      2.0e-3   0.0
4030212  40.00     0.0      1.6e-3   0.0
4030213  41.00     0.0      1.2e-3   0.0

```

```

4030214  42.00      0.0      0.0      0.0
4030215  1.0e6      0.0      0.0      0.0

```

```

*

```

```

*

```

```

*-----

```

```

*   Single Volume, Component 404   1/2" Pipe

```

```

*-----

```

```

*

```

```

*crdno   name      type
4040000   pipe404   snglvol

```

```

*

```

```

*cardno  area    length  volume
4040101  0.00072  2.0    0.0

```

```

*

```

```

*cardno  azim angle  incl. Angle  deltaz
4040102  0          0.0        0.0

```

```

*

```

```

*cardno  roughness  hyddia  tlpvbf
4040103  0.000005      0.03033  0001000

```

```

*

```

```

*cardno  ebt  pressure  temperature  equil-quality
4040200  003   12.594    70.0

```

```

*

```

```

*

```

```

*-----

```

```

* Checkvalve 405 2" void recirc line Check Valve SNGLVOL-404 to SNGLVOL-406

```

```

*-----

```

```

*

```

```

*   NAME      TYPE
4050000  chkv405  valve

```

```

*

```

```

*   FROM  TO    AREA  FLC  RLC  JUNC  FLAGS
4050101  404010000 406000000 0.00072  0.0  20.0  000100

```

```

*

```

```

*   CNRL LIQ  VAP  INTER(MASS FLOWS)
4050201  1  0.0  0.0    0.0

```

```

*

```

```

4050300  chkvlv

```

```

*

```

```

*   TYPE  INITPOS  CLPRES  LEAK
4050301  0          1      3.0    0.0

```

```

*

```

```

*

```

```

*-----

```

```

*   Single Volume, Component 406   1/2" Pipe

```

```

*-----

```

```

*
*crdno   name      type
4060000  pipe406    snlvol
*
*cardno  area     length  volume
4060101  0.00072    2.0    0.0
*
*cardno  azim angle  incl. Angle  deltaz
4060102  0          0.0          0.0
*
*cardno  roughness  hyddia      tlpvbfe
4060103  0.000005      0.03033    0001000
*
*cardno  ebt  pressure  temperature  equil-quality
4060200  003   12.594    70.0
*
*
*-----
* Branch 407 4"x4"x4" branch tee connecting SNGLVOL-406 (air line), PIPE-250, and
PIPE-300
*-----
*
*cardno   name           type
4070000   brnch407       branch
*
*cardno   number junctions      initial condition control
4070001   3                      1
*
*cardno  v.flowarea  vlength  v. h-ang  v-ang  delz  rough  dhy  tlpvbfe
4070101  0.0884        1.0    0.0 0.0 0.0 0.0 0.00015 0.3355 0010000
*
*cardno   ctl      pressure    temp  qual
4070200   003      12.594    70.0
*
* K thru floss = 20*f = 20 x .015 = 0.30
* K branch floss = 60*f = 60 x .015 = 0.90 - Based on water data and not air - need to
accommodate for air if needed
*cardno   from          to          area  floss  rloss  efvcchs
4071101  250010000  407000000  0.0884  0.0   0.0   0001000
4072101  406010000  407000000  0.00072  0.9   0.9   0011000
4073101  407010000  300000000  0.0884  0.3   0.3   0001000
*
*
*cardno   flowf      flowg      velj
4071201   0.0        0.0        0.0
4072201   0.0        0.0        0.0

```

```

4073201    0.0        0.0        0.0
*
*
*-----
*  Branch 310 4"x4"x2" branch tee connecting pipe-300, pipe-320,
*  and connected to pipe-700 via check valve 710 junction
*-----
*
*cardno    name        type
3100000    brnch310    branch
*
*cardno    number junctions    initial condition control
3100001    3                    1
*
*cardno v.flowarea vlength v. h-ang v-ang delz rough dhy tlpvbfe
3100101 0.0884    0.3355 0.0 0.0 0.0 0.0 0.00015 0.3355 0010000
*
*cardno    ctl        pressure    temp    qual
3100200    003        12.594    70.0
*
* K thru = 20 ft = 20 x .015 = 0.3
* K branch (2" pipe) = 60*ft = 60 x 0.019 = 1.14
* v = 1 upward oriented junction v = 2 downward oriented junction
* a = 1 abrupt area change
*cardno    from    to    area    floss    rloss    efvcchs
3101101 300010000 310000000 0.0884 0.0 0.0 0001120
3102101 310010000 320000000 0.0884 0.3 0.3 0001120
3103101 720010000 310010005 0.0233 1.14 1.14 0121100
*
*cardno    flowf        flowg        velj
3101201    0.0        0.0        0.0
3102201    0.0        0.0        0.0
3103201    0.0        0.0        0.0
*
*
*-----
*  Pipe-320 4" test loop line connecting Branch 310 to Branch 330
*-----
*
*cardno    name        type
3200000    pipe-320    pipe
*
*cardno    # Of Volumes
3200001    32
*
*cardno    Volume Flow Area    Volume Number

```

3200101	0.0884	32					
*							
*cardno	Junction Flow Area	Junction Number					
3200201	0.2006	31					
*							
*cardno	volume lengths	Volume Number					
3200301	0.340	10					
3200302	0.500	11					
3200303	0.657	21					
3200304	0.500	22					
3200305	0.340	32					
*							
*cardno	Volume	Volume Number					
3200401	0.0	32					
*							
*cardno	Vertical Angle	Volume Number					
3200601	0.0	10					
3200602	-45.0	11					
3200603	-90.0	21					
3200604	-45.0	22					
3200605	0.0	32					
*							
*cardno	rough	dhyd	Volume Number				
3200801	0.00015	0.3355	32				
*							
*cardno	kfor	krev	Junction Number				
3200901	0.00	0.00	9				
3200902	0.51	0.51	10				
3200903	0.00	0.00	20				
3200904	0.51	0.51	21				
3200905	0.00	0.00	31				
*							
*cardno	tlpvbfe	Volume Number					
3201001	0010000	32					
*							
*cardno	efvcahs	Junction Number					
3201101	0001000	20					
3201102	0000000	31					
*							
*cardno	ic	press	temp	qual	vol.		
3201201	3	12.594	70.0	0.0	0.0 0.0	10	
3201202	3	12.646	70.0	0.0	0.0 0.0	11	
3201203	3	12.752	70.0	0.0	0.0 0.0	12	
3201204	3	13.068	70.0	0.0	0.0 0.0	13	
3201205	3	13.384	70.0	0.0	0.0 0.0	14	
3201206	3	13.700	70.0	0.0	0.0 0.0	15	

```

3201207    3   14.016   70.0   0.0   0.0 0.0   16
3201208    3   14.332   70.0   0.0   0.0 0.0   17
3201209    3   14.648   70.0   0.0   0.0 0.0   18
3201210    3   14.964   70.0   0.0   0.0 0.0   19
3201211    3   15.280   70.0   0.0   0.0 0.0   20
3201212    3   15.694   70.0   0.0   0.0 0.0   21
3201213    3   15.820   70.0   0.0   0.0 0.0   22
3201214    3   15.872   70.0   0.0   0.0 0.0   32
*
*cardno      vel/flow
3201300      1
*
*cardno      liqflow  vaporf  interv  jun
3201301      0.0      0.0      0.0      31
*
*cardno      jct dh      beta  c    m    jun
3201401      0.0      0.0    1.0    1.0  31
*
*
*-----
* Branch 330 4"x4"x3" branch tee connecting pipe-320, pipe-340, and pipe-700
*-----
*
*cardno  name      type
3300000  brnch330  branch
*
*cardno  number junctions      initial condition control
3300001  3                      1
*
*cardno v.flowarea vlength v. h-ang v-ang delz rough dhy  tlpvbf
3300101 0.0884      0.5    0.0 0.0 0.0  0.0 0.00015 0.3355 0010000
*
*cardno  ctl      pressure      temp  qual
3300200  003      15.872      70.0
*
* K thru = 20 ft = 20 x .017 = 0.34
* K branch floss = 60 ft + 4 x 3 reduce = 1.02 + 0.506 = 1.526
* K branch rloss = 60 ft + 3 x 4 enlarge = 1.02 + 0.191 = 1.211
* * v = 1 upward oriented junction v = 2 downward oriented junction
* a = 1 abrupt area change
*cardno      from      to      area      floss  rloss  efvcchs
3301101 320010000 330000000 0.0884 0.0  0.0  0001120
3302101 330010000 340000000 0.0884 0.3  0.3  0001120
3303101 330010006 700000000 0.0513 1.526 1.211 0111100
*
*cardno  flowf      flowg      velj

```


3301201	0.0	0.0	0.0
3302201	0.0	0.0	0.0
3303201	0.0	0.0	0.0

*

*

*-----

* Pipe-700 3" x 2" void recirc test line connecting Branch 330 to chkvive 710

*-----

*

*cardno	name	type
7000000	pipe-700	pipe

*

*cardno	# Of Volumes
7000001	22

*

*cardno	Volume Flow Area	Volume Number
7000101	0.0513	6
7000102	0.0233	22

*

*cardno	Junction Flow Area	Junction Number
7000201	0.0513	6
7000202	0.0233	21

*

*cardno	volume lengths	Volume Number
7000301	0.260	6
7000302	0.27941	22

*

*cardno	Volume	Volume Number
7000401	0.0	22

*

*cardno	Vertical Angle	Volume Number
7000601	90.0	22

*

*cardno	rough	dhyd	Volume Number
7000801	0.00015	0.2557	6
7000802	0.00015	0.1722	22

*

*cardno	kfor	krev	Junction Number
7000901	0.00	0.00	5
7000902	0.992	0.309	6
7000903	0.00	0.00	21

*

*cardno	tlpvbfe	Volume Number
7001001	0010000	22

*

*cardno	efvchas	Junction Number
---------	---------	-----------------

7001101 0001000 21

*

*cardno	ic	press	temp	qual		vol.
7001201	3	15.815	70.0	0.0	0.0 0.0	1
7001202	3	15.703	70.0	0.0	0.0 0.0	2
7001203	3	15.590	70.0	0.0	0.0 0.0	3
7001204	3	15.478	70.0	0.0	0.0 0.0	4
7001205	3	15.365	70.0	0.0	0.0 0.0	5
7001206	3	15.253	70.0	0.0	0.0 0.0	6
7001207	3	15.112	70.0	0.0	0.0 0.0	7
7001208	3	14.971	70.0	0.0	0.0 0.0	8
7001209	3	14.830	70.0	0.0	0.0 0.0	9
7001210	3	14.690	70.0	0.0	0.0 0.0	10
7001211	3	14.549	70.0	0.0	0.0 0.0	11
7001212	3	14.408	70.0	0.0	0.0 0.0	12
7001213	3	14.268	70.0	0.0	0.0 0.0	13
7001214	3	14.127	70.0	0.0	0.0 0.0	14
7001215	3	13.986	70.0	0.0	0.0 0.0	15
7001216	3	13.846	70.0	0.0	0.0 0.0	16
7001217	3	13.705	70.0	0.0	0.0 0.0	17
7001218	3	13.564	70.0	0.0	0.0 0.0	18
7001219	3	13.423	70.0	0.0	0.0 0.0	19
7001220	3	13.283	70.0	0.0	0.0 0.0	20
7001221	3	13.142	70.0	0.0	0.0 0.0	21
7001222	3	13.001	70.0	0.0	0.0 0.0	22

*

*cardno	vel/flow
7001300	1

*

*cardno	liqflow	vaporf	interv	jun
7001301	0.0	0.0	0.0	21

*

*cardno	jct dh	beta	c	m	jun
7001401	0.0	0.0	1.0	1.0	21

*

*-----

* Checkvalve 710 2" void recirc line Check Valve -pipe 700 to pipe 720

*-----

*

* NAME	TYPE
7100000 chkv710	valve

*

* This check vlave junction can be simulated as a lift check valve (1/2 lb spring socket)

* $K \text{ loss} = 600 \cdot \text{ft} = 600 \cdot 0.019 = 11.4$

* FROM	TO	AREA	FLC	RLC	efvcahs
7100101 700010000	720000000	0.0233	11.4	11.4	0000000

```

*
*   CNRL LIQ VAP INTER(MASS FLOWS)
7100201 1 0.0 0.0 0.0
*
7100300 chkvlv
*
*   TYPE INITPOS CLPRES LEAK
7100301 0 1 0.596 0.0
*
* -----
* Pipe-720 2" void recirc test line connecting CHKVLV 810 to BRANCH 410
* -----
*
*cardno  name      type
7200000  pipe-720    pipe
*
*cardno  # Of Volumes
7200001  4
*
*cardno  Volume Flow Area      Volume Number
7200101  0.0233                    4
*
*cardno  Junction Flow Area    Junction Number
7200201  0.0233                  3
*
*cardno  volume lengths        Volume Number
7200301  0.200                  3
7200302  0.311                  4
*
*cardno  Volume                Volume Number
7200401  0.0                    4
*
*cardno  Vertical Angle        Volume Number
7200601  90.0                  4
*
*cardno  rough    dhyd        Volume Number
7200801  0.00015  0.1722      4
*
*cardno  kfor     krev        Junction Number
7200901  0.00     0.00        3
*
*cardno  tlpvbf     Volume Number
7201001  0010000    4
*
*cardno  efvchas    Junction Number
7201101  0001000    3

```

```

*
*cardno  ic    press  temp  qual          vol.
7201201   3    12.958  70.0  0.0  0.0  0.0    1
7201202   3    12.871  70.0  0.0  0.0  0.0    2
7201203   3    12.785  70.0  0.0  0.0  0.0    3
7201204   3    12.717  70.0  0.0  0.0  0.0    4
*
*cardno          vel/flow
7201300          1
*
*cardno          liqflow  vaporf  interv  jun
7201301          0.0      0.0      0.0      3
*
*cardno          jct dh      beta  c    m    jun
7201401          0.0      0.0    1.0  1.0    3
*
* -----
*  Pipe-340 6" test loop return line connecting Branch 330 to Valve 450
* -----
*
*cardno  name      type
3400000  pipe-340   pipe
*
*cardno  # Of Volumes
3400001  14
*
*cardno  Volume Flow Area      Volume Number
3400101  0.0884                    14
*
*cardno  Junction Flow Area     Junction Number
3400201  0.0884                    13
*
*cardno  volume lengths         Volume Number
3400301  0.350                      14
*
*cardno  Volume                 Volume Number
3400401  0.0                      14
*
*cardno  Vertical Angle         Volume Number
3400601  0.0                      14
*
*cardno  rough    dhyd         Volume Number
3400801  0.00015    0.3355        14
*
*cardno  kfor      krev         Junction Number
3400901  0.0          0.0          13

```

```

*
*cardno      tlpvbf      Volume Number
3401001      0010010      14
*
*cardno      efvcchs      Junction Number
3401101      0001000      13
*
*cardno      ic  press  temp  qual  W5  W6      vol.
3401201      3   15.774  70.0  0.0   0.0  0.0      14
*
*cardno      vel/flow
3401300      1
*
*cardno      liqflow  vaporf  interv      jun
3401301      0.0      0.0      0.0          13
*
*cardno      jct dh      beta  c    m      jun
3401401      0.0      0.0  1.0  1.0      13
*
*
*-----
*  Valve 350 - 4 " loop test line isolation valve Pipe 340 to Pipe 360
*-----
*
*      NAME  TYPE
3500000  vlv450  valve
*
* Crane Eqn 2-6  $k = (29.9 d^2 / C_v)^2 = 0.02399$ 
* Where  $C_v = 3129$  gpm/psi
*      FROM  TO      AREA  FLC  RLC  efvcchs
3500101 340010000 360000000 0.0884 0.024 0.024 0001000
*
*      CNRL LIQ  VAP  INTER(MASS FLOWS)
3500201 1  0.0  0.0      0.0
*
*      TYPE
3500300  trpvlv
*
*      TRIP
3500301  501
*
*-----
*  Pipe-360 6" test loop return line connecting Branch 430 to Valve 450
*-----
*
*cardno      name      type

```

```

3600000    pipe-360    pipe
*
*cardno    # Of Volumes
3600001      7
*
*cardno    Volume Flow Area    Volume Number
3600101      0.0884            4
3600102      0.2006            7
*
*cardno    Junction Flow Area    Junction Number
3600201      0.0884            3
3600202      0.2006            6
*
*cardno    volume lengths    Volume Number
3600301      0.506            4
3600302      0.900            7
*
*cardno    Volume    Volume Number
3600401      0.0            7
*
*cardno    Vertical Angle    Volume Number
3600601      0.0            7
*
*cardno    rough    dhyd    Volume Number
3600801      0.00015    0.3355    4
3600801      0.00015    0.5054    7
*
*cardno    kfor    krev    Junction Number
3600901      0.0    0.0    2
3600902      0.931    0.309    3
3600902      0.0    0.0    6
*
*cardno    tlpvbf    Volume Number
3601001      0010000    7
*
*cardno    efvchas    Junction Number
3601101      0001000    6
*
*cardno    ic    press    temp    qual    W5    W6    vol.
3601201      3    15.943    70.0    0.0    0.0    0.0    7
*
*cardno    vel/flow
3601300      1
*
*cardno    liqflow    vaporf    interv    jun
3601301      0.0    0.0    0.0    6

```

```

*
*cardno    jct dh    beta  c    m    jun
3601401    0.0      0.0   1.0   1.0   6

* -----
* Pipe-460 6" test loop return line connecting Branch 430 to Valve 450
* -----
*
*cardno    name      type
4600000    pipe-460  pipe
*
*cardno    # Of Volumes
4600001    4
*
*cardno    Volume Flow Area      Volume Number
4600101    0.2006                4
*
*cardno    Junction Flow Area    Junction Number
4600201    0.2006                3
*
*cardno    volume lengths        Volume Number
4600301    0.890                 4
*
*cardno    Volume                Volume Number
4600401    0.0                   4
*
*cardno    Vertical Angle        Volume Number
4600601    0.0                   4
*
*cardno    rough    dhyd        Volume Number
4600801    0.00015    0.5054    4
*
*cardno    kfor     krev        Junction Number
4600901    0.0      0.0         3
*
*cardno    tlpvbf     Volume Number
4601001    0010000    4
*
*cardno    efvchas    Junction Number
4601101    0001000    3
*
*cardno    ic  press  temp  qual  W5  W6    vol.
4601201    3   15.943  70.0  0.0   0.0  0.0    4
*
*cardno    vel/flow
4601300    1

```

```

*
*cardno      liqflow  vaporf  interv  jun
4601301      0.0      0.0      0.0      3
*
*cardno      jct dh    beta    c      m      jun
4601401      0.0      0.0      1.0    1.0    3
*
*-----
* Branch 630 6"x6"x6" branch tee connecting pipe-640, pipe-620,and pipe-460
*-----
*
*cardno      name      type
6300000      brnch630    branch
*
*cardno      number junctions      initial condition control
6300001      3                      1
*
*cardno v.flowarea vlength v. h-ang v-ang delz rough dhy tlpvbf
6300101 0.2006 1.0 0.0 0.0 0.0 0.0 0.00015 0.5054 0010000
*
*cardno      ctl      pressure      temp      qual
6300200      003      15.943      70.0
*
* K thru = 20 ft = 20 x .015 = 0.3
* K branch floss = 60 ft = 60 x .015 = 0.9
*cardno      from      to      area      floss      rloss      efvcahs
6301101 630010000 640000000 0.2006 0.00 0.00 0001000
6302101 620010000 630000000 0.2006 0.30 0.30 0001000
6303101 630010000 460000000 0.2006 0.90 0.90 0001000
*
*
*cardno      flowf      flowg      velj
6301201      0.0      0.0      0.0
6302201      0.0      0.0      0.0
6303201      0.0      0.0      0.0
*
*-----
* Pipe-640 6" return line from 8" test loop dead end
*-----
*
*cardno      name      type
6400000      pipe-640    pipe
*
*cardno      # Of Volumes
6400001      12
*

```


*cardno	Volume Flow Area	Volume Number					
6400101	0.2006	12					
*							
*cardno	Junction Flow Area	Junction Number					
6400201	0.2006	11					
*							
*cardno	volume lengths	Volume Number					
6400301	0.506	12					
*							
*cardno	Volume	Volume Number					
6400401	0.0	12					
*							
*cardno	Vertical Angle	Volume Number					
6400601	0.0	12					
*							
*cardno	rough	dhyd	Volume Number				
6400801	0.00015	0.5054	12				
*							
*cardno	kfor	krev	Junction Number				
6400901	0.0	0.0	5				
6400902	0.45	0.45	6				
6400903	0.0	0.0	11				
*							
*cardno	tlpvbfe	Volume Number					
6401001	0010000	12					
*							
*cardno	efvchas	Junction Number					
6401101	0001000	11					
*							
*cardno	ic	press	temp	qual	W5	W6	vol.
6401201	3	15.943	70.0	0.0	0.0	0.0	12
*							
*cardno	vel/flow						
6401300	1						
* W1 = mass flow ic							
*							
*cardno	liqflow	vaporf	interv		jun		
6401301	0.0	0.0	0.0		11		
*							
*cardno	jct dh	beta	c	m	jun		
6401401	0.0	0.0	1.0	1.0	11		
*							
*							
* -----							
* Pipe-620 6" return line - 6" test loop branch630 to 4" test loop branch610							

```

*-----
*
*cardno  name      type
6200000  pipe-620  pipe
*
*cardno  # Of Volumes
6200001  5
*
*cardno  Volume Flow Area      Volume Number
6200101  0.2006                     5
*
*cardno  Junction Flow Area   Junction Number
6200201  0.2006                     4
*
*cardno  volume lengths      Volume Number
6200301  0.506                      3
6200302  0.574                      5
*
*cardno  Volume              Volume Number
6200401  0.0                      5
*
*cardno  Vertical Angle      Volume Number
6200601  0.0                      5
*
*cardno  rough      dhyd      Volume Number
6200801  0.00015      0.5054      5
*
*cardno  kfor      krev      Junction Number
6200901  0.0      0.0      4
*
*cardno  tlpvbf      Volume Number
6201001  0010000      5
*
*cardno  efvchas      Junction Number
6201101  0001000      4
*
*cardno  ic  press  temp  qual  W5  W6      vol.
6201201  3  15.943  70.0  0.0  0.0  0.0      5
*
*cardno  vel/flow
6201300  1
*
*cardno  liqflow  vaporf  interv      jun
6201301  0.0      0.0      0.0      4
*
*cardno  jct dh      beta  c      m      jun

```

```

6201401      0.0      0.0  1.0  1.0    4
*
*
*-----
*  Branch 610 6"x6"x6" branch tee connecting pipe-620, pipe-600,and pipe-300
*-----
*
*cardno      name          type
6100000      brnch610      branch
*
*cardno      number junctions      initial condition control
6100001      3                      1
*
*cardno v.flowarea v.length v. h-ang v-ang delz rough dhy tlpvbf
6100101 0.2006    1.0  0.0 0.0 0.0  0.0 0.00015 0.5054 0010000
*
*cardno      ctl      pressure      temp      qual
6100200      003      16.215      70.0
*
* K thru = 20 ft = 20 x .015 = 0.3
* K branch floss = 60 ft = 60 x .015 = 0.9
*cardno      from      to          area      floss      rloss      efvcahs
6101101 610010000    620000000    0.2006    0.00    0.00    0001000
6102101 610010000    600000000    0.2006    0.30    0.30    0001000
6103101 360010000    610000000    0.2006    0.90    0.90    0001000
*
*
*cardno      flowf      flowg      velj
6101201      0.0      0.0      0.0
6102201      0.0      0.0      0.0
6103201      0.0      0.0      0.0
*
*
*-----
*  Pipe-600 6" return line to Tank 900
*-----
*
*cardno      name      type
6000000      pipe-600    pipe
*
*cardno      # Of Volumes
6000001      50
*
*cardno      Volume Flow Area      Volume Number
6000101      0.2006      50
*

```

*cardno	Junction Flow Area		Junction Number		
6000201	0.2006		49		
*					
*cardno	volume lengths		Volume Number		
6000301	0.506		50		
*					
*cardno	Volume		Volume Number		
6000401	0.0		50		
*					
*cardno	Vertical Angle		Volume Number		
6000601	0.0		28		
6000602	90.0		38		
6000603	0.0		46		
6000604	-90.0		50		
*					
*cardno	rough	dhyd	Volume Number		
6000801	0.00015	0.5054	50		
*					
*cardno	kfor	krev	Junction Number		
6000901	0.00	0.00	27		
6000902	0.45	0.45	28		
6000903	0.00	0.00	37		
6000904	0.45	0.45	38		
6000905	0.0	0.0	45		
6000906	0.45	0.45	46		
6000907	0.0	0.0	49		
*					
*cardno	tlpvbfe		Volume Number		
6001001	0010000		50		
*					
*cardno	efvchas		Junction Number		
6001101	0001000		49		
*					
*cardno	ic	press	temp	qual	vol.
6001201	3	15.943	70.0	0.0	0.0 0.0 28
6001202	3	15.724	70.0	0.0	0.0 0.0 29
6001203	3	15.505	70.0	0.0	0.0 0.0 30
6001204	3	15.286	70.0	0.0	0.0 0.0 31
6001205	3	15.067	70.0	0.0	0.0 0.0 32
6001206	3	15.848	70.0	0.0	0.0 0.0 33
6001207	3	14.629	70.0	0.0	0.0 0.0 34
6001208	3	14.410	70.0	0.0	0.0 0.0 35
6001209	3	14.191	70.0	0.0	0.0 0.0 36
6001210	3	13.972	70.0	0.0	0.0 0.0 37
6001211	3	13.753	70.0	0.0	0.0 0.0 46

6001212	3	13.972	70.0	0.0	0.0	0.0	47
6001213	3	14.191	70.0	0.0	0.0	0.0	48
6001214	3	14.410	70.0	0.0	0.0	0.0	49
6001215	3	14.629	70.0	0.0	0.0	0.0	50

*

*cardno vel/flow

6001300 1

*

*cardno liqflow vaporf interv jun

6001301 0.0 0.0 0.0 49

*

*cardno jct dh beta c m jun

6001401 0.0 0.0 1.0 1.0 49

*

*-----

* Single Junction, Component 605 6" Test Return Pipe 600 to Tank 100 -

*-----

*

*cardno name type

6050000 jun605 sngljun

*

*cardno from to area kf. kr. efvchas

6050101 600010000 9000000000 0.2006 1.0 0.5 0001000

*

*cardno vel/flow liquid vapor int-face

6050201 1 0.0 0.0 0.0

*

*-----

* Pipe-250 6" x 4" line to BRANCH 407 (air line injection)

*-----

*

*cardno name type

2500000 pipe-250 pipe

*

*cardno # Of Volumes

2500001 18

*

*cardno Volume Flow Area Volume Number

2500101 0.2006 12

2500102 0.0884 18

*

*cardno Junction Flow Area Junction Number

2500201 0.2006 11

2500202 0.0884 17

*

*cardno	volume lengths	Volume Number	
2500301	0.506	12	
2500302	0.350	18	
*			
*cardno	Volume	Volume Number	
2500401	0.0	18	
*			
*cardno	Vertical Angle	Volume Number	
2500601	0.0	18	
*			
*cardno	rough	dhyd	Volume Number
2500801	0.00015	0.5054	12
2500802	0.00015	0.3355	18
*			
*cardno	kfor	krev	Junction Number
2500901	0.0	0.0	5
2500902	0.45	0.45	6
2500903	0.0	0.0	10
2500904	0.93	0.309	11
2500905	0.0	0.0	17
*			
*cardno	tlpvbfe	Volume Number	
2501001	0010000	18	
*			
*cardno	efvchas	Junction Number	
2501101	0001000	17	
*			
*cardno	ic	press	temp
2501201	3	12.594	70.0
*			
*cardno	ic	qual	W5
2501201	3	0.0	0.0
*			
*cardno	ic	W6	vol.
2501201	3	0.0	18
*			
*cardno	vel/flow		
2501300	1		
*			
*cardno	liqflow	vaporf	interv
2501301	0.0	0.0	0.0
*			
*cardno	jun		
2501301	17		
*			
*cardno	jct dh	beta	c
2501401	0.0	0.0	1.0
*			

* TMDPVOL 900 establishes sink pressure			

*			
*crdno	name	type	
9000000	tank900	tmdpvol	
*			

```

*cardno  area  length  volume
9000101  10.0   1.0e6   0.0
*
*cardno  azim angle  incl. Angle  deltaz
9000102  0           0.0         0.0
*
*cardno  roughness  hyddia  pvbfe
9000103  0.00015       0.0      00010
*
*cardno  ebt      trip      search var
9000200  003
*
*cardno  time      Pressure  Temperature
9000201  0.00         14.7      70.0
9000202  5.00         14.7      70.0
9000203  1.0e6        14.7      70.0
*
.
* end of input

```

Appendix D – VRS Model Results

Appendix D.1. Mass Flow Rate Results

Figure D.1. Mass flow rate behavior for scenario one (4x4x3-inch, $Fr = 0.81$).

Figure D.2. Mass flow rate behavior for scenario two (4x4x3-inch, $Fr = 0.96$).

Figure D.3. Mass flow rate behavior for scenario three (4x4x3-inch, $Fr = 1.29$).

Figure D.4. Mass flow rate behavior for scenario four (4x4x3-inch, $Fr = 1.60$).

Figure D.5. Mass flow rate behavior for scenario five (6x6x4-inch, $Fr = 0.81$).

Figure D.6. Mass flow rate behavior for scenario six (6x6x4-inch, $Fr = 1.10$).

Figure D.7. Mass flow rate behavior for scenario seven (6x6x4-inch, $Fr = 1.38$).

Figure D.8. Mass flow rate behavior for scenario eight (6x6x4-inch, $Fr = 1.60$).

Appendix D.2. Void Fraction Results

Figure D.9. Void fraction behavior for scenario one (4x4x3-inch, $Fr = 0.81$).

Figure D.10. Void fraction behavior for scenario two (4x4x3-inch, $Fr = 0.96$).

Figure D.11. Void fraction behavior for scenario three (4x4x3-inch, $Fr = 1.29$).

Figure D.12. Void fraction behavior for scenario four (4x4x3-inch, $Fr = 1.60$).

Figure D.13. Void fraction behavior for scenario five (6x6x4-inch, $Fr = 0.81$).

Figure D.14. Void fraction behavior for scenario six (6x6x4-inch, $Fr = 1.10$).

Figure D.15. Void fraction behavior for scenario seven (6x6x4-inch, $Fr = 1.38$).

Figure D.16. Void fraction behavior for scenario eight (6x6x4-inch, $Fr = 1.60$).

Appendix E – VRS Simulation and Experimental Void Fraction Validation

Figure E.1. Void fraction validation for scenario one (4x4x3-inch, $Fr = 0.81$).

Figure E.2. Void fraction validation for scenario two (4x4x3-inch, $Fr = 0.96$).

Figure E.3. Void fraction validation for scenario three (4x4x3-inch, $Fr = 1.29$).

Figure E.4. Void fraction validation for scenario four (4x4x3-inch, $Fr = 1.60$).

Figure E.5. Void fraction validation for scenario five (6x6x4-inch, $Fr = 0.81$).

Figure E.6. Void fraction validation for scenario six (6x6x4-inch, $Fr = 1.10$).

Figure E.7. Void fraction validation for scenario seven (6x6x4-inch, $Fr = 1.38$).

Figure E.8. Void fraction validation for scenario eight (6x6x4-inch, $Fr = 1.60$).