Thermally Insulating Coating for Steel Drill Pipe

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by

Matt McCaffrey

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Author: Matt A. McCaffrey

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Prof. Blair London	______________________________
Faculty Advisor	Signature
Prof. Richard Savage	______________________________
Department Chair	Signature

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Abstract

A 5/16 in thick, 6 in x 6 in steel plate was used as a simple analog to 4 inch grade “S” steel drill pipe. Ethylene tetraflouroethylene (ETFE) applied as a powder coating was selected as the desired thermally insulating coating because of its excellent chemical resistance, maximum service temperature of 300°C, its thermal conductivity of 0.238 W/m-K, and for its ability to be applied in thicknesses of up to 80 mils. A powder primer coat of approximately 2 mils was applied using a conventional corona electrostatic powder sprayer, and then the high build topcoat was applied directly over the dry primer coat using the same technique to a thickness of about 10 mils. The primer and first topcoat were then cured at an elevated temperature. Subsequent layers of topcoat were hot flocked until a final coating thickness of 60 mils was achieved. To determine the effective thermal conductivity of the coated steel, an apparatus consisting of three contact thermocouples, a hot plate, and polystyrene foam panels was assembled. The hot plate was heated to a constant temperature, then the room temperature coated steel plate was placed under the polystyrene insulation on the hot plate, coated side up. The temperature of both sides of the coated plate was then measured for 30 minutes. The heat flux was then calculated through the bare steel plate. This heat flux value was used to calculate the effective thermal conductivity of the coated plates. The average measured effective thermal conductivities for 40 mil, 60 mil, and 80 mil coatings were 0.82 W/m-K, 0.61 W/m-K, and 0.69 W/m-K respectively.

Keywords: Materials Engineering, Drill Pipe, Coatings, Thermoplastic, Thermal Conductivity, Powder Coating, Petroleum, Drilling Mud

Introduction

Crude oil is mainly produced through drilling oil wells to tap the deposits trapped by the local lithology. Today's society is dependent on crude oil; in 2010 the world's consumption neared 90,000 barrels per day[1]. In order to sustain the world's growing consumption, oil companies must increase their effective output. This means drilling more wells, whether exploratory, or to increase the output of a known oil field. The drilling of oil wells is one step in a complicated process to harvest energy-dense hydrocarbons known as crude oil. Modern drilling operations can be complex, utilizing directional drilling and cutting-edge technology to access previously unreachable deposits.

Today drilling is mainly conducted using rotationally powered drill heads. Drill heads used in oil well drilling can be categorized into two main groups, fixed cutter and rotary cones (Figure 1). Fixed cutter bits often use polycrystalline diamond compact bits that are attached to carbide inserts. Rotary cone bits use steel or tungsten carbide inserts for their cutting edges[2]. The drill string is all of the components downhole, at the bottom of a well, needed to drill successfully (Figure 2).

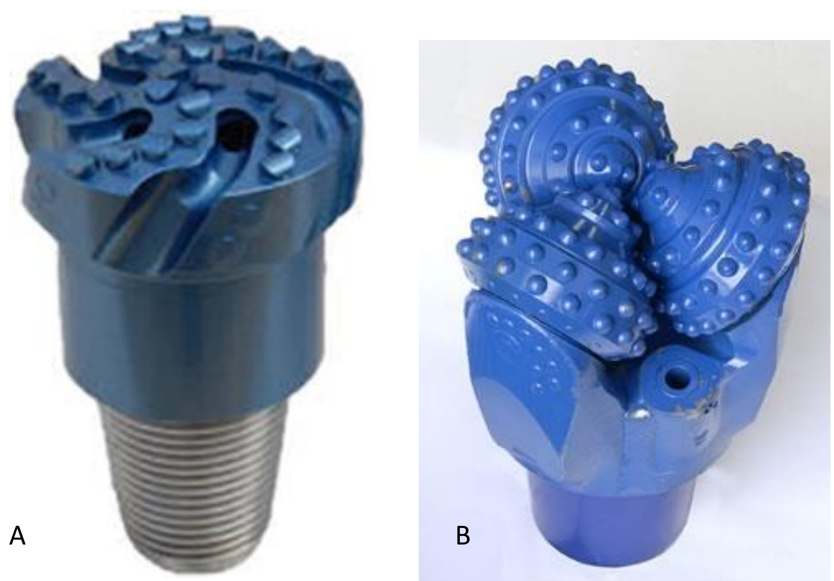

Figure 1: Pictured is A is a tri-cone rotary bit[3], in B is a fixed cutter bit[4]. Both are steel bodied with carbide inserts. These bits grind and cut into the earth, and are lubricated and cooled by drilling mud.

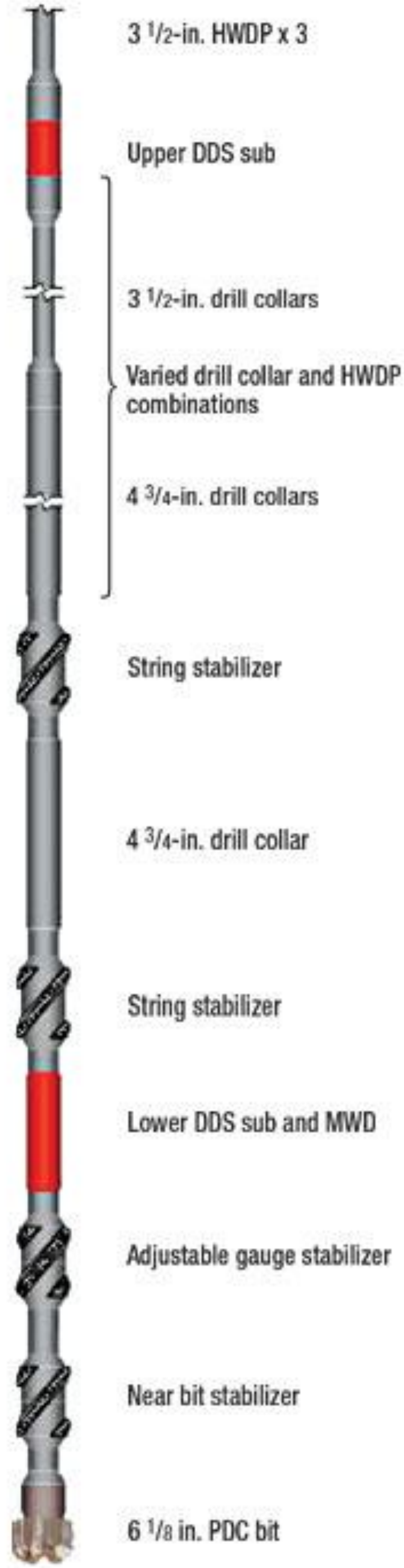

Figure 2: An example of a bottom hole drill string assembly, note the Drill String Dynamics sensor (DDS) in red. These sensors working life can be reduced by exposure to the high ambient temperatures.

In addition to drill heads, there are many other components that function downhole to drive and support the drilling process. This series of components is often referred to as the bottom hole assembly[5]. These motors, stabilizers, steering systems, measurement and logging devices all must withstand the same extreme environments as the drill head. This can lead to unique engineering challenges where high performance materials must be utilized. The components in a bottom hole assembly vary from well to well, depending on the unique lithology encountered during each drill[6].

The drilling process creates cuttings which need to be removed from the well. Drilling fluids, often referred to as drilling mud, are used to lubricate the drill head and carry away cuttings (Figure 3). Drilling mud has several important functions. First, for the mud to carry away drill

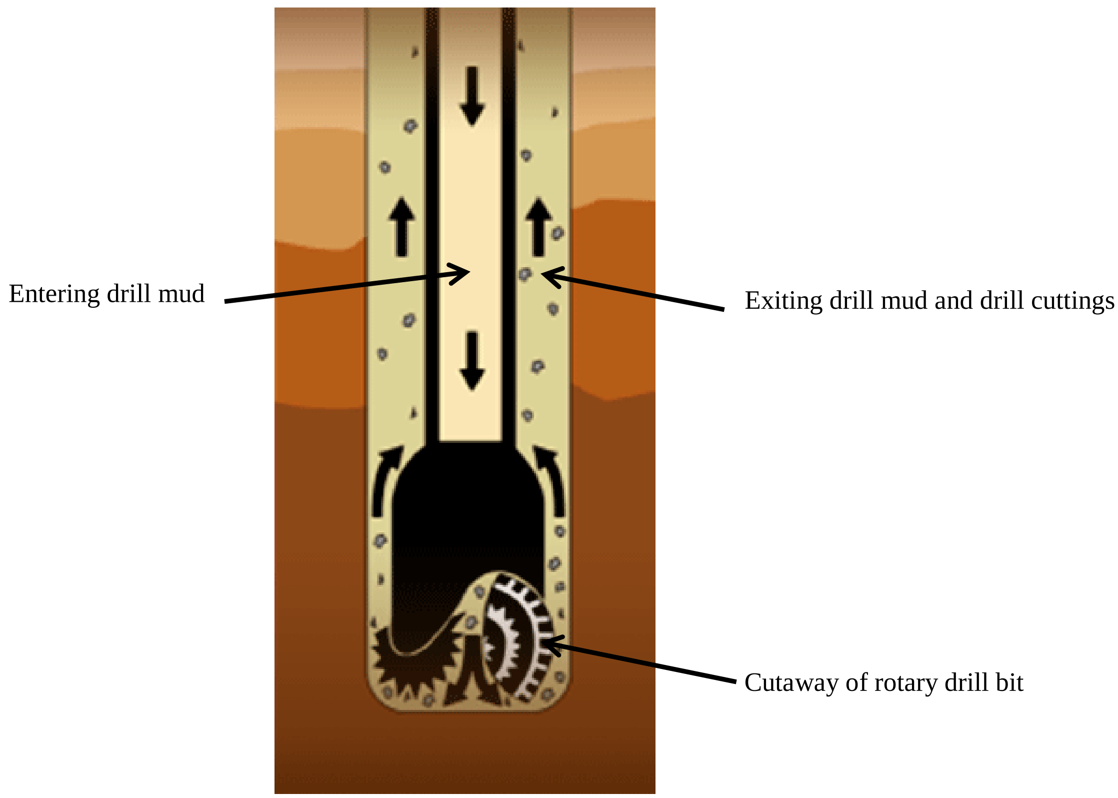

Figure 3: A rotary drill bit at work, with drilling mud carrying away the cuttings produced by the bit[2]. The drilling mud serves as a lubricant and coolant for the drill head**.**

cuttings effectively, it must be dense so that the cuttings remain suspended through their journey out of the well. Clays like Wyoming Bentonite are added to increase viscosity and density[7]. The density of the mud also contributes to the pressure applied to the formation the well bore travels through. This pressure keeps the hydrocarbons from exiting the formation while the drill bore is

completed. The drill mud also decreases stresses in drill piping by adding buoyancy, as the long drill pipe strings can become extremely long and heavy. Special additives are added to drill mud to ensure that the surrounding formations remain unclogged so the oil is able to flow. The drilling mud needs to be piped all the way to the drill head for it to serve the function of removing drill cuttings and lubrication. Drill Cool Systems (Bakersfield, CA) uses a 4 inch Grade S-135 drill pipe. This drill piping is manufactured with compliance to API spec 5D[8].

The lithology and geothermal gradients encountered when drilling can vary drastically depending on the location and geology of the area being probed (Figure 4). The high formation temperatures experienced by the downhole materials, motors, electronics, and steering tools all contribute to reduced life cycles and efficiency.

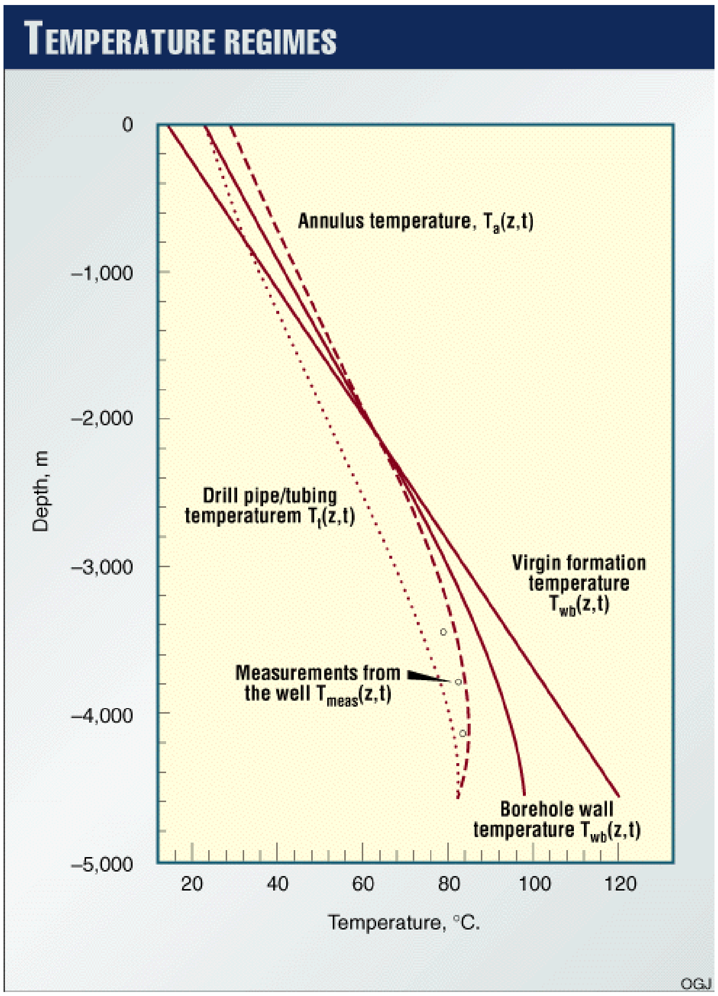

Figure 4: A geothermal gradient diagram, showing the temperatures of the drill pipe, and borehole wall from a typical drill well. Temperatures reach 120°C in the virgin formation of this drill hole[9].

The high ambient temperatures experienced by downhole components can lead to many problems. Electrically operated sensors or motors become less efficient due to the general decrease in electrical conductivity of metals as temperatures rise. Oil wells also tend to be a highly corrosive environment, with drill pipes and machinery coming into contact with chemicals known to cause corrosion such as H_2S and chlorides. The high downhole temperatures sometimes reaching 200°C, negatively affect components' life cycles, as corrosion generally tends to increase with increasing temperature[10].

Realistic Constraints

A proposed coating must be economic. For an insulating coating to be economic, it must be able to withstand a range of environments so that replacement or maintenance of the coating is kept to a minimum. The material cost of the coating must also cost less than $60/foot of drill pipe. Oil wells often use thousands of meters of drill pipe, so the costs add up quickly. But avoiding the replacement of downhole components will save money and time for the companies that utilize the insulated drill pipe.

The proposed coating must comply with manufacturability constraints. The coating needs to be applied on a large scale, on many thousands of sections of existing drill pipe, each 32 feet long, and be able to be performed on an industrial scale. The coating must be composed from readily available materials, so that the scale of the processing is feasible.

Experimental Procedure

Material Selection

A material selection process was performed using CES EduPack 2012 Software[11]. Limits were put into place on the material's durability, chemical resistance, and maximum service temperature. Maximum service temperature and thermal conductivity were chosen as the axes for the plot because they are both critical to the performance of the coating (Figure 5).

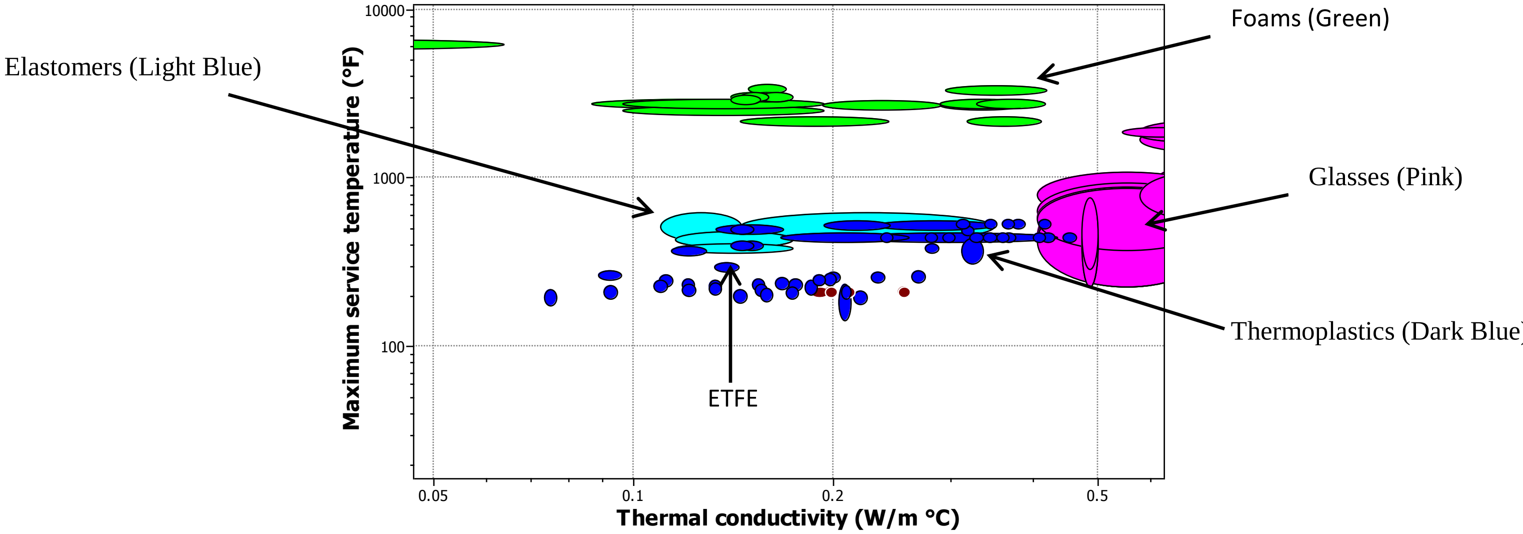

Figure 5: The CES material selection chart used to narrow down the materials of consideration. Maximum service temperature and thermal conductivity make up the axes because of their critical importance to the function of the coating.

The CES plot produced a selection of materials that could be viable coating materials. Other considerations such as price, availability, and possible coating processes were taken into account. Ethylene tetrafluoroethylene (ETFE) was chosen as the coating material because of its outstanding chemical resistance (excellent durability in fresh and salt water, weak and strong acids, weak and strong alkalis, and organic solvents), abrasion resistance, high maximum service temperature (150ºC)[11], and its ability to be powder coated to thicknesses greater than 60 mils[12].

Process Selection

Electrostatic powder coating was chosen as the most viable coating process. Electrostatic powder coating is a method of applying a coating to a grounded material by spraying charged, powdered material onto a work piece. The work piece must be cleaned to expose the bare surface; this is usually accomplished using abrasive spraying like sandblasting. Next the work piece is electrically grounded, and the powder is mixed with compressed air into a fluidized like state, then is sprayed through a nozzle where it is charged by a high voltage, low amperage electrode as it exits towards the grounded work piece[13]. The electrostatic attraction between the charged powder and the work piece results in an even coating of the powder over the surface of the work piece (Figure 6). Next the coated work piece is baked at an elevated temperature to cure the coating. Subsequent layers can be coated while the work piece is still hot from curing; this process is called hot flocking.

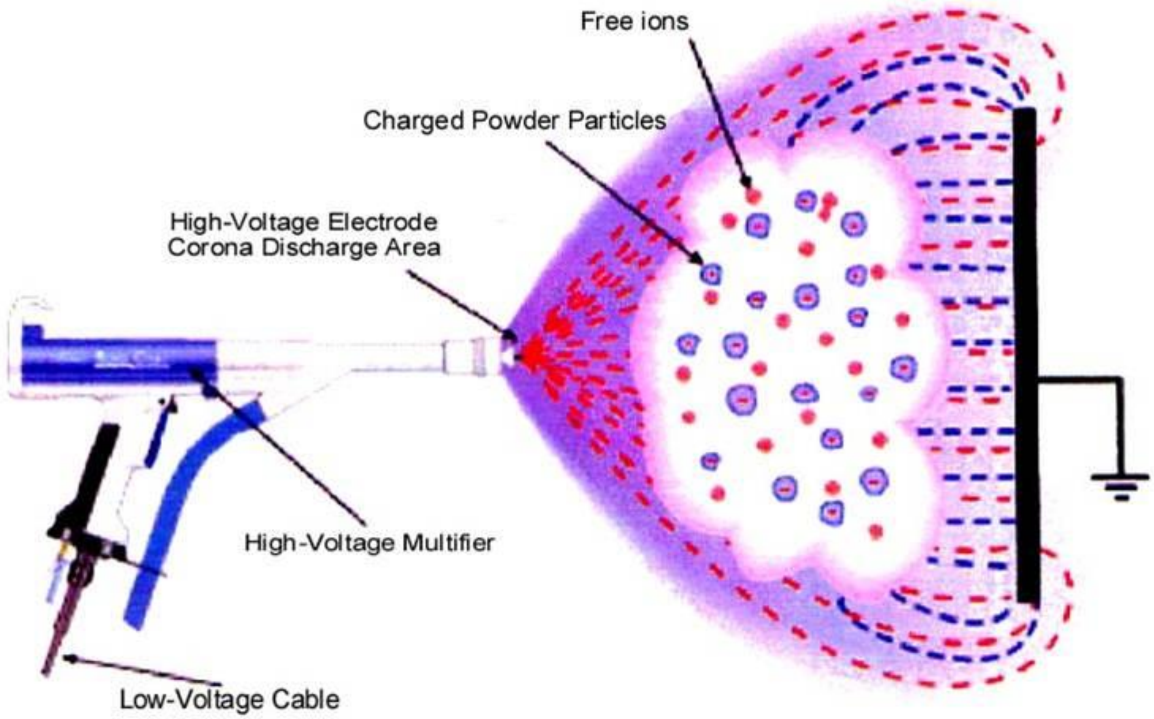

Figure 6: A typical electrostatic powder coating process, where charged powder particles are drawn to the grounded work piece, forming an even coating.

Powder coating can also produce much thicker coatings than similar liquid processes without running or sagging, this ability is important to this application because of the thicknesses needed to reach adequate insulation.

Coating Application

An analog to steel drill piping was needed to simplify application of the coating and thermal insulation testing. A 6 in x 6 in plain carbon steel plate 5/16in thick was chosen as an analog to the steel drill piping. The ETFE topcoat and primer was supplied by Dupont. The coating was applied using an electrostatic powder coating gun. The coating parameters were 24-35 kV electrostatic charge, 1.5-2 bar air pressure. A third party company performed the powder coating. First a thin 2 mil primer coat was applied, then the plate was baked in an oven at 220°F for 10 minutes to cure. Next the first topcoat layer was applied to a thickness of about 10 mils, and then cured at 580°F for 30 minutes. While the plate was still hot from the oven, subsequent layers of topcoat were hot flocked onto the plate, and then cured until thicknesses of 40, 60, or 80 mils

(Figure 7). Drill Cool Systems recommended a coating thickness of 60 mils to optimize flow through the drill piping. Alternative thicknesses were chosen to see how the effective thermal conductivity of the plate would change with coating thickness while remaining close to the optimal thickness.

Figure 7: A 6in x 6in steel plate with an 80 mil thick ETFE coating, applied using electrostatic powder coating. The green color comes from the primer layer, while the topcoat is semi-translucent, with a glossy finish.

Testing Procedure

A method of testing the effective thermal conductivity of the coated steel plates was developed and constructed. The experimental setup consisted of a hot plate acting as a steady heat source, polystyrene foam insulation to minimize environmental interaction, SA2-K type adhesive molded silicone thermocouples attached to the coated or uncoated steel plates, and an Omega thermocouple datalogger. The room temperature steel plates were placed on the preheated hot plate, and the temperature of both the bottom and top surface (coated/uncoated) of the steel plate was recorded for 30 minutes using Omega datalogger software (Figure 8).

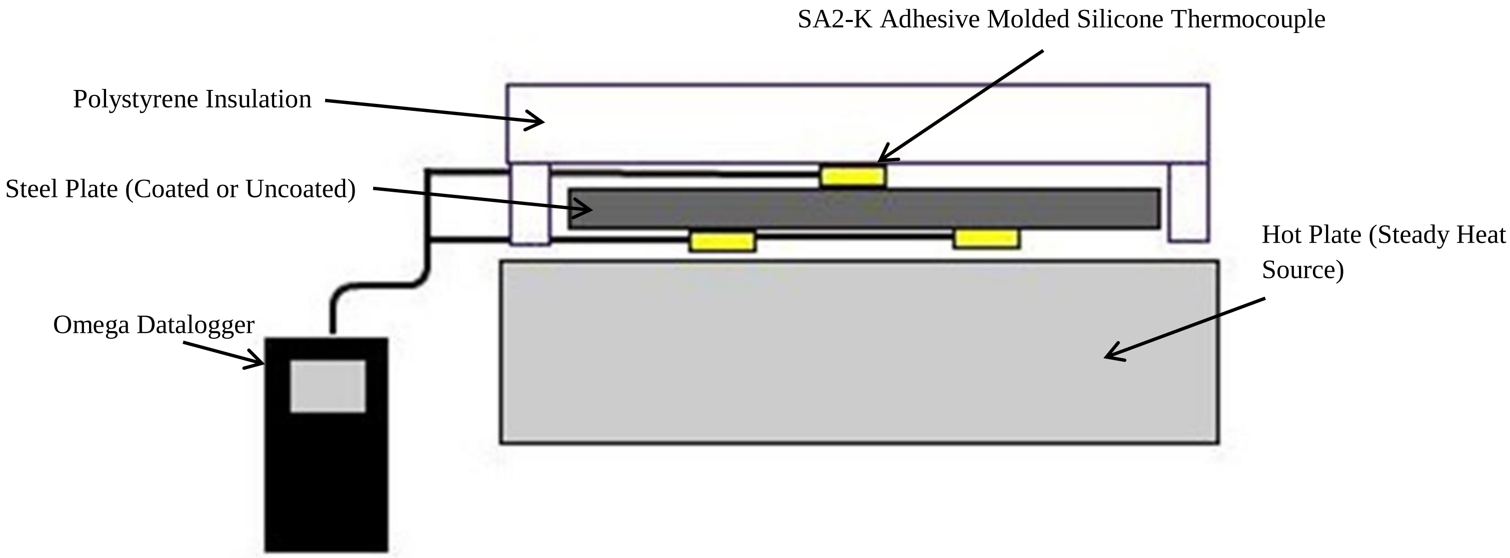

Figure 8: The experimental setup, consisting of SA2-K Omega thermocouples, insulation, Datalogger and hot plate.

An uncoated steel plate was tested first on the experimental apparatus. From the heat transfer experiment on the uncoated steel plate, a heat flux value was established using Fourier's law of heat transfer:

Eq. 1 $$Q = kA\frac{\Delta T}{\Delta x}$$

Where Q is the heat flux in Watts, k is the thermal conductivity in W/m-K, ΔT is the temperature difference across the plate in °C, and Δx is the total thickness of the plate in meters. In the uncoated steel plate experiment, k, A, and Δx are all known. The test reveals the ΔT across the plate at any given time (Figure 9), and using the ΔT values, a heat flux across the steel plate can be found.

Next the coated steel plates were each tested 3 times. From the data gathered during these tests, the effective thermal conductivity (k) of the plates was calculated. The effective k values of the plates were found using Fourier's law (eq. 1). To find the effective k value, it was assumed that the heat flux through the uncoated steel would be the same through the coated steel plates since the dominate material is the steel. Using the known heat flux through the uncoated steel, thermal conductivities for each of the coated plates were calculated using the measured temperature difference through the plates (Figures 10, 11, 12).

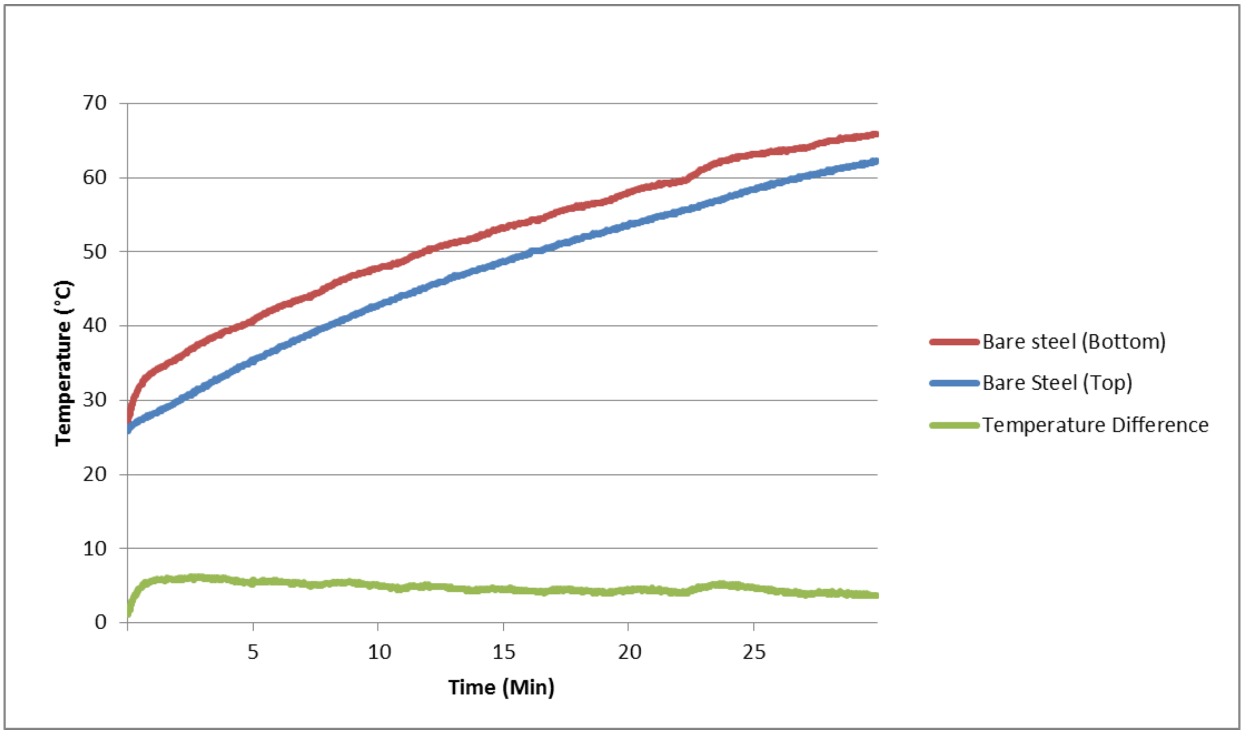

Figure 10: The heat transfer data for the uncoated steel plate. Note the maximum temperature reached about 65°C and the temperature difference was about 5°C. This is one test run chosen as a representative sample of the raw data.

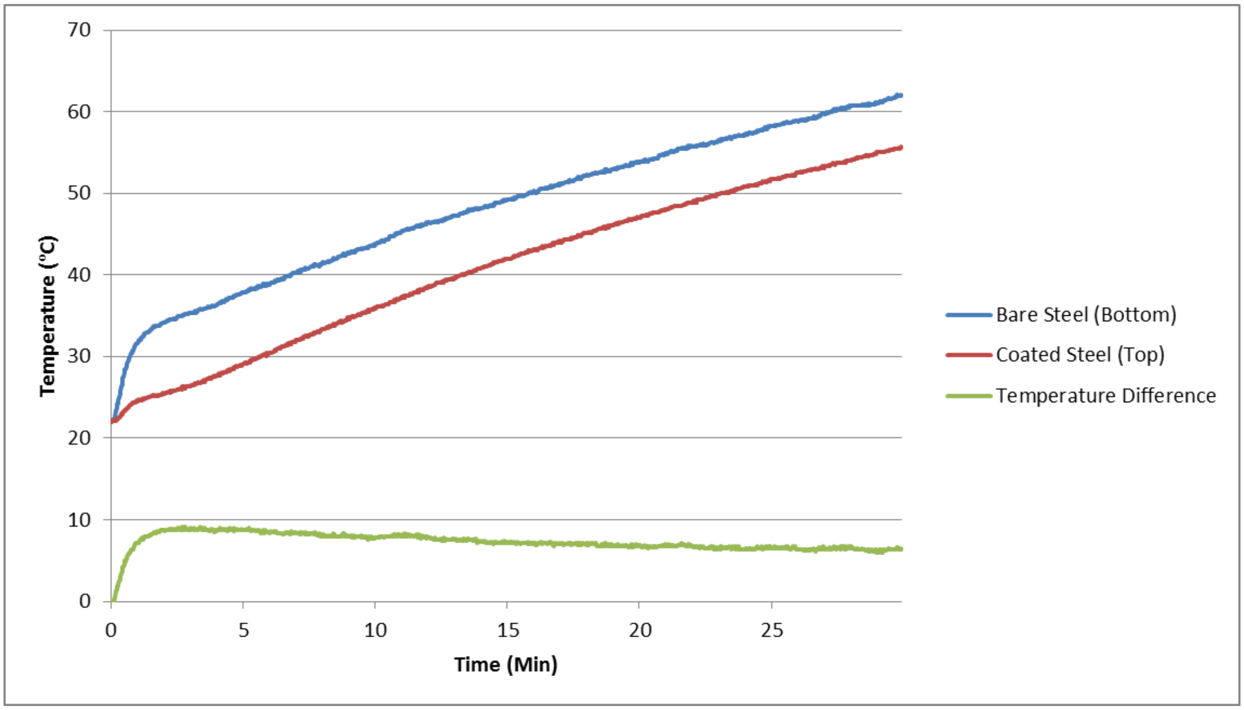

Figure 9: The heat transfer data for the 40 mil ETFE coated steel plate. The temperature difference ran from about 9-7°C. This is one test run chosen as a representative sample of the raw data.

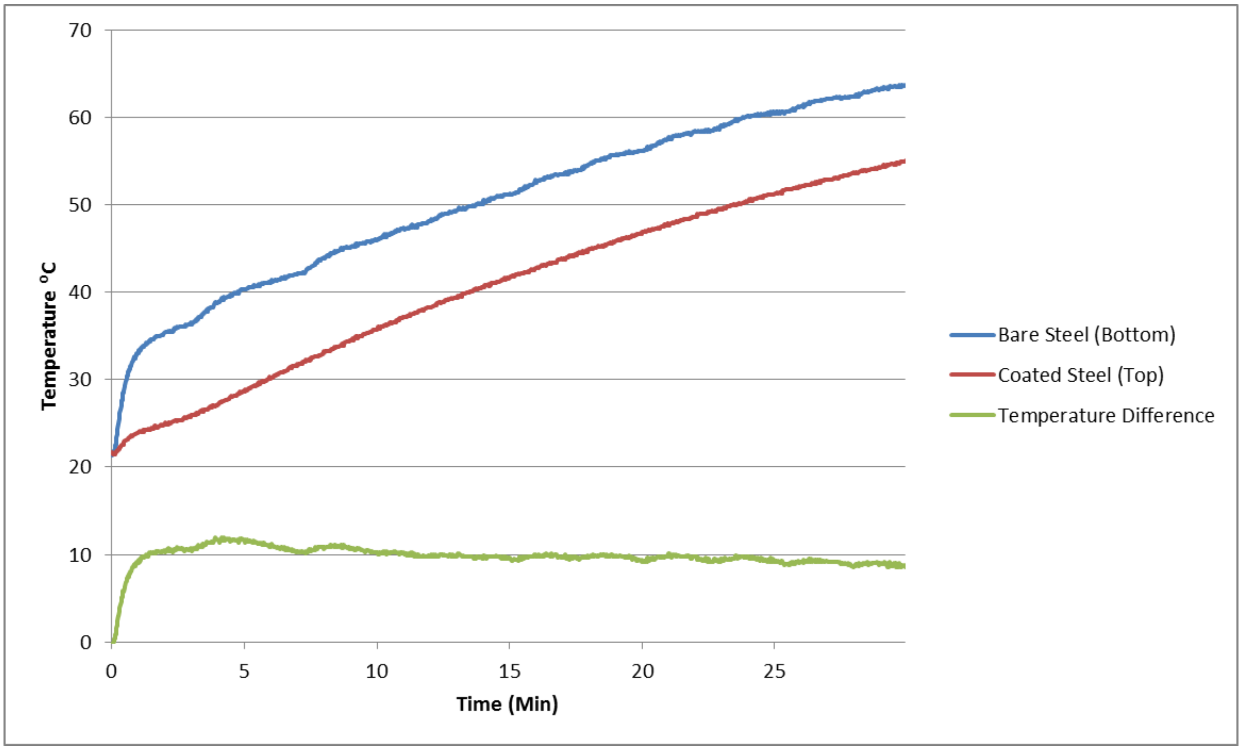

Figure 12: The heat transfer data for the 60 mil ETFE coated steel plate. The temperature difference ran from about 12-9°C. This is one test run chosen as a representative sample of the raw data.

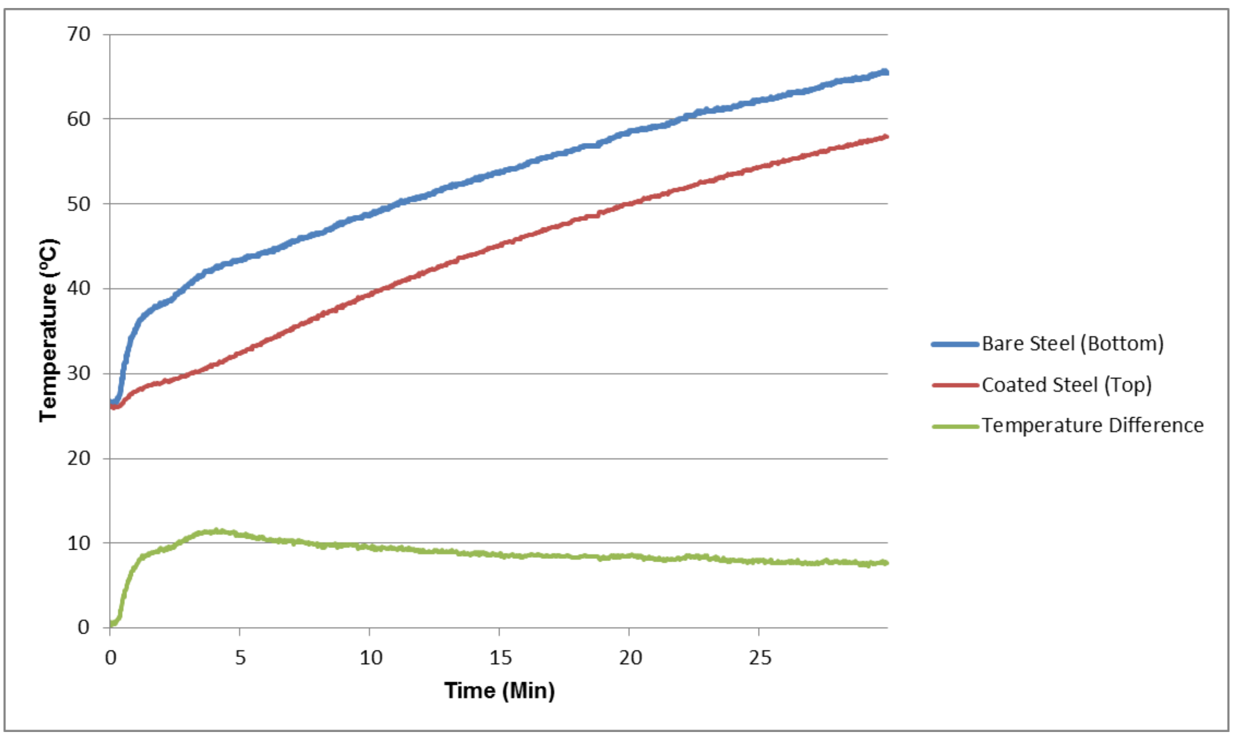

Figure 11: The heat transfer data for the 80 mil ETFE coated steel plate. The temperature difference ran from about 8-12°C. This is one test run chosen as a representative sample of the raw data.

The theoretical effective thermal conductivities for the coated steel samples were determined by adding the respective thermal resistivities of the steel and ETFE coating in series[14] (Table I).

Eq 2 $$R = {}^{\Delta x}/_{k}$$

Where C is the thermal resistance, k is the thermal conductivity of the material, and Δx is the thickness of the material. Once the thermal resistances of the steel plate and coating were calculated, they were added in series to find the combined resistivity.

Table I: Thermal Conductivities

Material	Thermal Conductivity (W/m-K)
ETFE	0.238
Steel	52

Eq 3. $$R_{Steel} + R_{ETFE} = R_{Total}$$

Using the total resistivity found from Eq. 3, the theoretical effective thermal conductivity of the coated plates were found using Eq. 2. These theoretical values were compared to the calculated values from the heat transfer experiments.

Results

The results from the heat transfer data were processed using Microsoft Excel, and the thermal conductivities were found using Eq. 3. The standard deviation of the thermal conductivities from each test was found to check for variation (Table II).

Table II: Results of Heat Transfer Testing

Sample	Average Calculated Effective Thermal Conductivity (W/m-K)	Average Experimental Effective Thermal Conductivity (W/m-K)	Standard Deviation (W/m-K)
Uncoated	52	-	-
40 mil	2.04		
Test 1		0.78	0.061
Test 2		0.82	0.078
Test 3		0.86	0.075
60 mil	1.45		
Test 1		0.58	0.063
Test 2		0.62	0.069
Test 3		0.63	0.077
80 mil	1.17		
Test 1		0.65	0.067
Test 2		0.71	0.078
Test 3		0.73	0.074

Discussion

The theoretical thermal conductivities had a strong correlation with the thickness of the coating, with a R^2 value of 0.96. The measured thermal conductivities on the other hand had no correlation with the thickness of the coating, with a R^2 value of 0.30 (Figure 13).

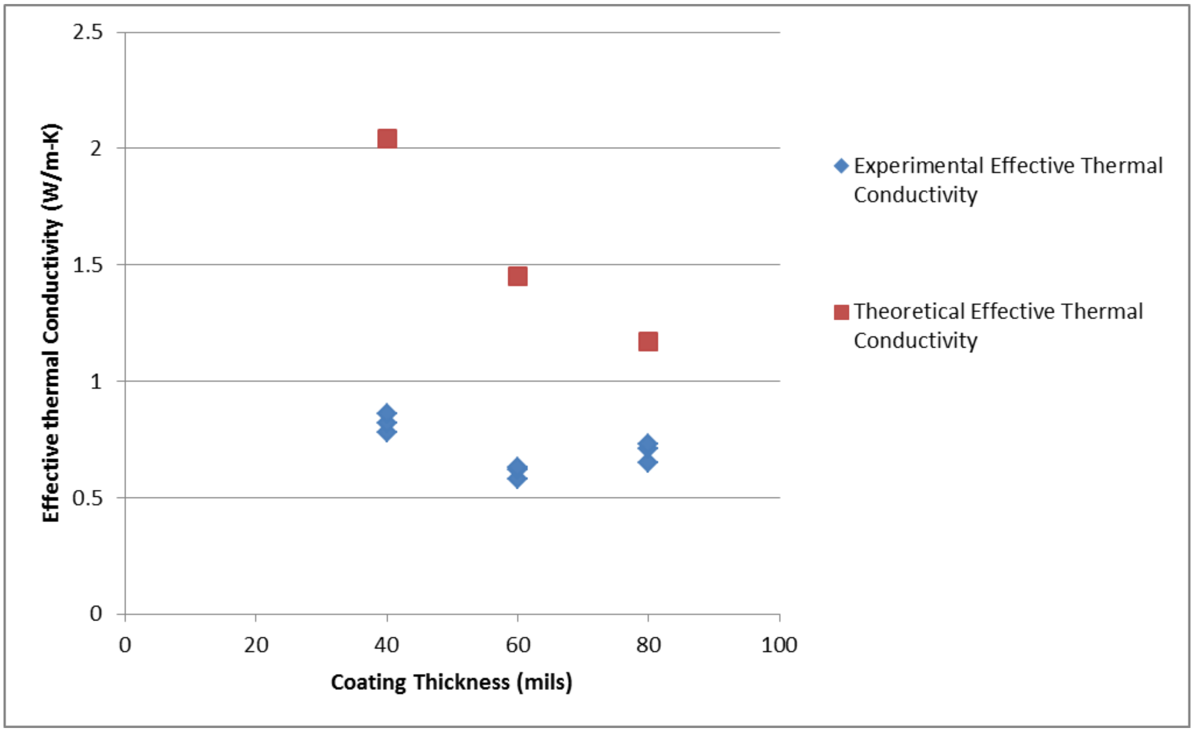

Figure 13: The theoretical and experimental effective thermal conduct ivies of the ETFE coated steel plates with linear regression for both sets of data.

The weak correlation of the measured values and the large difference between the calculated values may be explained by the interface between the coating and the steel plate. This interface and its thermal properties are affected by many different factors such as surface deformations, surface cleanliness, and any contact pressure the interface may have experienced[15].

Another reason for the weak correlation could be the experimental setup. The insulation was not perfect, there was sure to be some air flow that would have acted as a thermal sink, not allowing the plate to reach an equilibrium temperature. The hot plate could also have been more accurate so that the experiments could be more repeatable.

Regardless of there not being a correlation between coating thickness and effective thermal conductivity, the fact that the measured values were significantly lower than the calculated

values is a positive result. This means that the coating could function as an insulator better than expected, and a tradeoff between coating thickness and thermal conductivity could be found at a lower thickness than expected, meaning optimum flow rates in the drill pipe while maintaining adequate insulation.

Conclusion

- Electrostatic powder coating was a viable option to apply coatings of 40, 60, and 80 mils.
- There is a no correlation between coating thickness and the measured effective thermal conductivity, this may be due to the unknown variables of the steel-coating interface
- The measured effective conductivities were significantly lower than the calculated values. Both the 40 and 60 mil coating’s effective thermal conductivity was about 60% lower than the calculated. The 80 mil coating’s effective thermal conductivity was about 45% lower than the calculated. Using this information, a thin coating could optimize the drill mud flow rate while maintaining adequate insulation in the drill pipe.

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