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Modelling Heat Losses in a Tar Sand Formation during Thermal Recovery Processes

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Abstract: *Heat losses to adjacent formations jeopardize the efficiency of thermal recovery operations. Predicting these energy losses is important in the design of a thermal recovery project. The case study is a steam flood project where heat losses from a tar sand formation is mathematically modeled based on pertinent assumptions. The heat loss model was developed using the law of conservation of energy, with heat energy as a function of the properties of the tar sand formation and the heat-carrying fluid. Solutions of this model were obtained using the MATLAB software. Sensitivity analyses revealed that the rate of heat loss to the adjacent strata increased/decreased depending on the variation of the steam and tar sand formation properties. A variation of some properties had no significant effect on the rate of heat losses. Thus, it is vital in advance to gather adequate information especially of the tar sand formation so as to prepare an injection fluid whose properties would minimize heat losses to the cap and base rocks. This would increase the mobility of the oil and extend the life of the production well(s).*
Keywords: *Heat Losses, Steam flooding, Tar Sand, Thermal Recovery, Unconventional resources.*

I. Introduction

Hydrocarbons have remained the primary source of energy of the world's economy. Most of the earth's potential oil and gas reserves have already been discovered and are currently under rapid depletion. With the present decline of most proven conventional oil and gas reserves, more attention has been turned towards the large volume of naturally-occurring unconventional oil reserves. One of such reserves is the tar sand.

Tar sand is any consolidated or unconsolidated rock that contains a hydrocarbon material with a gas-free viscosity, measured at reservoir temperature, greater than 10,000mPaS, or that contains a hydrocarbon material that is extractable from mined or quarried rock. this definition excludes other fossil fuels of higher viscosity – the coals, oil shales and solid bitumen. It, however, includes tarry oil deposits in rocks other than sandstones.

Compilation of the largest known tar sand deposits indicate that about 20 deposits contain between them more than $3 * 10^{11}$ m^3 of oil-in-place. About 98 percent of this volume is contained in sands located in Venezuela, the Canadian province of Alberta and the Soviet Union [1]. The recovery technology that would be employed in producing these oil sand depends on their depth, with the near-surface deposits extracted using open cast mining and the deeper deposits (usually depths greater than 75m) requiring in situ recovery techniques like fireflooding, steam stimulation and most commonly, steamflooding.

A major setback of the steamflood process is heat losses to the adjacent formations i.e. cap and base rocks. This often reduces the efficiency of the steamflood operation. This work presents mathematical models for the prediction of heat losses into adjacent formations during a steamflooding operation, incorporating the factors that contribute to more losses and how they may be varied to make a steamflood process more effective.

1.1 Predicting Heat Losses

The thermal recovery method considered in this study is steamflooding. Heat losses from the formation have remained a perpetual challenge to petroleum engineers. It has led to reduction in the temperature of steam, which reverts the process to waterflooding[2]. Additionally, the sweep area of the reservoir is small as compared to the entire volume of the reservoir, resulting in lower oil mobility ratios. Thus, a lot of research has been done to predict heat losses into adjacent formations.

Pacheco and Farouq-Ali[3] formulated a comprehensive mathematical model of steam injection into a reservoir to include a simultaneous calculation of the steam pressure and quality. The model amongst other things took into account heat losses by radiation, conduction and convection and consisted of two coupled non-linear differential equations that were solved iteratively.

Zolotukhin[4] adopted the concept of overall heat transfer coefficient to represent the heat loss from a reservoir into the adjacent strata and developed a new approach in which he proposed that the overall heat transfer coefficient is not constant, unlike other concepts, but changes with respect to time for processes such as hot water or steam injection, or In-situ combustion.

Shum and Haynes[5] developed a model to calculate the transfer of heat into (and from) the cap and base rocks, and necessarily the temperature distribution in the rocks. The principle of superposition was applied in this method due to its simplicity as an effective solution method, and computer storage and time.

Unlike most mathematical methods based on the frontal displacement of oil by steam over the full thickness of an oil sand, in which solutions were usually displayed as curves that relate the percentage of total heat retained in the oil zone to a dimensionless time, Vogel's [6] method of heat requirements for steam floods utilizes equations for linear heat flow from an infinite plane, which has proven to be more accurate. Although this method specifically deals with providing accurate estimates in cases such as for the ultimate heat requirements and for desirable returns of heat injection, they are useful for estimating all heat losses.

Chiu and Thakur[7] developed a wellbore heat loss and pressure (WHAP) model. It considers the injection of steam or liquid water into a directional well under injection conditions. The model can predict heat losses under changing injection conditions. The injection rate, pressure, temperature and steam quality at the wellhead may change with time. The superposition principle is used to determine the rate of heat losses and, ultimately, the bottom-hole conditions of the fluid.

Farouq-Ali[8] developed a model based on mass and momentum balances in the wellbore and on heat balance in the wellbore and surrounding media, in which heat loss to the surrounding functions was treated vigorously.

Abdurrahman et al [9] proposed a model for linear and radial reservoir geometries in which hot and cold water were injected into porous media.

In representing steam process with vacuum models, Stegemeier et al [10] simulated cap and base rock heat losses by cementing ¼ -in glass plates together with clear silicon potting compound. Before the cement has hardened, the plates are loaded to extrude excess compound, leaving only a thin cement layer. This thin layer allows sufficient thermal expansion to avoid cracking of the blocks during the thermal experiment.

II. Mathematical Model Development

2.1 Basic Assumptions

The following pertinent assumptions were made for the mathematical description of heat losses during steam injections for the thermal recovery of oil from tar sands:

1. The reservoir is homogeneous and of constant thickness.
2. Steam is injected at a constant rate, temperature, pressure and quality. It is either saturated or under-saturated but not super-saturated.
3. Steam flows uniformly into the pay zone and in the linear direction only. The steam front is assumed to be vertical spanning through the entire pay.
4. The pressure drop in the steam zone is assumed to be negligible and therefore steam zone temperature is essentially equal to the injection temperature.
5. Mass flow rate and condensed water is the same from the injection well to the steam front.
6. Variation of the injected steam quality in the vertical direction is negligible.
7. Initially, the bounding formations are at the same temperature as the reservoir.
8. Heat losses into the cap and base rocks are equal.
9. The model does not consider fluid flow.

2.2 Model Development

Considering an elemental volume of the tar sand formation as shown in Fig.1, the energy balance for heat flow in and out of the volume is given by:

$$\dot{Q}_{in} - \dot{Q}_{out} = \dot{Q}_{losses} \tag{1}$$

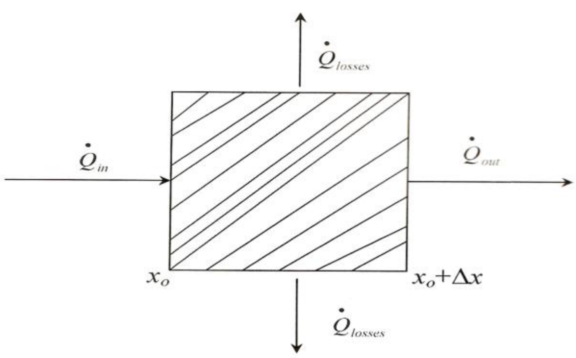

Figure 1: Elemental volume of tar sand

Heat transfer into the tar sand formation occurs by conduction and convection. Thus the rate of heat injection $\dot{Q}_{in}$ is given by:

$$\dot{Q}_{in} = (\dot{Q}_{in})_{conduction} + (\dot{Q}_{in})_{convection} \tag{2}$$

Similarly, heat leaves the elemental volume through conduction and convection to the adjacent formations. Mathematically, $\dot{Q}_{out}$ is given by:

$$\dot{Q}_{out} = (\dot{Q}_{out})_{conduction} + (\dot{Q}_{out})_{convection} + \dot{Q}_{losses} \tag{3}$$

The rate of heat stored, $\dot{Q}_{storage}$ is given by:

$$\dot{Q}_{storage} = Q_r + Q_f \tag{4}$$

Where:

$$Q_r = m_r c_r (T_f - T_i)$$
$$= \rho_r c_r \left[(1-\phi)\Delta v\right]\left(T_f - T_i\right) \tag{5}$$

Also:

$$Q_f = m_f c_f (T_f - T_i)$$
$$= \rho_f c_f \phi \, \Delta v (T_f - T_i) \tag{6}$$

Substituting Equations (5) and (6), into (4), $Q_{storage}$ becomes:

$$Q_{storage} = [\rho_r c_r (1-\phi) + \rho_f c_f \quad]\Delta v (T_f - T_i) \tag{7}$$

The rate of heat storage will then be given by:

$$\frac{d\dot{Q}_{storage}}{dt} = [\rho_r c_r (1-\phi) + \rho_f c_f \phi]\Delta v \frac{dT}{dt} \tag{8}$$

Let Q_{in} be mainly by convection, Equation (2) then becomes:

$$\dot{Q}_{in} = (\dot{Q}_{in})_{convection} \tag{9}$$

Applying Newton's law of cooling/heating:

$$\dot{Q}_{in} = K_h A (T_f - T_i)\Big|_{x_o} \tag{10}$$

Similarly, let Q_{in} be mainly by conduction. Applying Fourier's law of conduction, [11] we have for Q_{out}:

$$\dot{Q}_{out} = -kA\frac{dT}{dx}\bigg|_{x_o+\Delta x} + \dot{Q}_{losses} + k_h A (T_f - T_i)\bigg|_{x_o+\Delta x} \tag{11}$$

Substituting Equations (8), (10) and (11) into equation (1), we have:

$$k_h A (T_f - T_i)\Big|_{x_o} + kA\frac{dT}{dt}\bigg|_{x_o+\Delta x} - \dot{Q}_{losses} - k_h A (T_f - T_i)\bigg|_{x_o+\Delta x} = \{\rho_r c_r (1-\phi) + \rho_f c_f \phi\}\Delta v \frac{dT}{dx} \tag{12}$$

Making Q_{losses} the subject of the formula:

$$\dot{Q}_{losses} = k_h A (T_f - T_i)\Big|_{x_o} + kA\frac{dT}{dt}\bigg|_{x_o+\Delta x} - k_h A (T_f - T_i)\bigg|_{x_o+\Delta x} - \{\rho_r c_r (1-\phi) + \rho_f c_f \phi\}\Delta v \frac{\partial T}{\partial x} \tag{13}$$

Using Taylor's expansion series to expand Equation (13), we have:

$$kA\frac{dT}{dx}\bigg|_{x_o+\Delta x} = \left(kA\frac{\partial T}{\partial x} + kA\Delta x \frac{d^2 T}{dx^2}\right) \tag{14}$$

$$K_h A\left(T_f - T_i\right)\Big|_{x_o+\Delta x} = \left[K_h A\left(T_f - T_i\right) + K_h A \Delta x \frac{dT}{dx}\right]\Bigg|_{x_o} \tag{15}$$

Substituting Equations (14) and (15) into Equation (13), we have:

$$\dot{Q}_{losses} = -\left[\rho_r c_r (1-\phi) + \rho_f c_f \phi\right]\Delta v \frac{\partial T}{\partial t} + K_h A (T_f - T_i)\Big|_{x_o} + \left(kA\frac{dT}{dx} + kA\Delta x \frac{d^2T}{dx^2}\right) - \left[K_h A (T_f - T_i)\Big|_{x_o} + K_h A\Delta x \frac{dT}{dx}\right] \quad (16)$$

$$= -\left[\rho_r c_r (1-\phi) + \rho_f c_f \phi\right]\Delta v \frac{dT}{dt} + kA\frac{dT}{dx} + kA\Delta x \frac{d^2T}{dx^2} - K_h A\Delta x \frac{dT}{dx} \quad (17)$$

$$= -\left[\rho_r c_r (1-\phi) + \rho_f c_f \phi\right]\Delta v \frac{dT}{dt} + (k - K_h \Delta x) A \frac{dT}{dx} + kA\Delta x \frac{d^2T}{dx^2} \quad (18)$$

Let:

$$B = \rho_r c_r (1-\phi) + \rho_f c_f \phi \quad (19)$$

Equation (18) then becomes:

$$\dot{Q}_{losses} = -B\Delta v \frac{dT}{dt} + (k - K_h \Delta x) A \frac{dT}{dx} + kA\Delta x \frac{d^2T}{dx^2} \quad (20)$$

But:

$$\Delta v = A\Delta x \quad (21)$$

Thus, Equation (20) becomes:

$$\dot{Q}_{losses} = -BA\Delta x \frac{dT}{dt} + (k - K_h \Delta x) A \frac{dT}{dx} + kA\Delta x \frac{d^2T}{dx^2}$$

$$= A\left[(k - K_h)\frac{dT}{dt} - B\Delta x \frac{dT}{dx} + k\Delta x \frac{d^2T}{dx^2}\right] \quad (22)$$

III. Results and Discussion

The mathematical model for heat losses was analyzed using computer software called MATLAB and sensitivity analysis were performed using the data represented in Tables 1 and 2.

3.1 Results of Sensitivity Analyses of the Model

The following results were obtained after analysis of the reservoir data presented in tables 1 and 2.

Table 1: Reservoir Distance and Temperature Distribution

Distance, x (ft)	**Temp., T (^oF)**	**Distance, x (ft)**	**Temp., T (^oF)**	**Distance, x (ft)**	**Temp., T (^oF)**
120	2200	310	2405	510	2695
160	2300	330	2440	600	2699
200	2350	370	2500	620	2701
250	2370	420	2600	660	2710
300	2400	500	80		

Table 2: Rock and fluid Properties

Property	**Value**
Rock density, lbm/cu.ft	1100
Specific heat capacity of Rock, Btu/lb-^oF	7.25
Density of fluid, lbm/cu.ft	999.5
Specific heat capacity of fluid, Btu/lb-^oF	7.25
Thermal conductivity of Rock, ft^2/hr	1.7307
Convective heat transfer coefficient, Btu/hr.ft^2-^oF	0.978
Heat area of reservoir, (ft)	3000

3.1.1 Sensitivity Analysis of Fluid Density on Heat Loss

The density of the injected fluid was varied over several ranges i.e. low, medium and high against the heat losses from the formation. It is evident from Fig. 2* that there is no significant change in the formation heat loss with a variation of the density of the injection. Thus, density change of the injection fluid has a uniform effect on the heat loss, rate, and Q_{losses}.

3.1.2 Sensitivity Analyses of Thermal Conductivity on Heat Loss

For tar sand formations with varying thermal conductivities, it was observed that lower thermal conductivities had lower rates of heat losses. Additionally, an increase in the thermal conductivity of the formation resulted in an increase in the heat losses from that formation. These observations reveal that formations with higher thermal conductivities have higher rates of heat losses and vice versa. A variation of k with Q_{losses} is shown in Fig. 3.

3.1.3 Sensitivity Analysis for Porosity Changes

Another factor on which the heat losses from a tar sand formation depend is the porosity of the formation. After a variation of the formation porosity, it was observed from Fig. 4 that as the porosity of the formation increases so does the heat losses from the formation to the adjacent strata.

3.1.4 Sensitivity Analysis for Specific Heat Capacity of Rock

Fig. 5 shows a relationship between the heat losses from a tar sand formation and its specific heat capacity. From the figure, the lower the specific heat capacity, the higher are the heat losses and vice versa. Thus, a tar sand formation with a higher heat capacity would be ideal if heat losses must be minimized.

3.1.5 Sensitivity Analysis for Heat Loss against Area Change

Solution to the mathematical model revealed that as the area of the steam front increases, there is a variation (unsteadiness) in the rate of heat losses. From Fig. 6, it could be seen that at a particular point, the heat losses in the respective areas remained constant. However, as the steam front continues to move, a reversal takes place – heat losses drop as the steam front contacts the lower areas of the formation.

3.1.6 Sensitivity Analysis of Distance against Temperature

Fig. 7 shows a relationship between the reservoir temperature over a wide range of the reservoir. As the steam front advances in the pay zone, an increase was observed in the reservoir temperature.

3.1.7 Sensitivity Analysis for Temperature on Distance

After analyzing the effect of the linear distance on the temperature of the reservoir, it was observed that as shown in Fig. 8, the formation temperature increases as the linear distance of the reservoir increases.

3.1.8 Sensitivity Analysis of Heat Loss against Distance

Fig. 9 relates the rate of heat loss to the linear direction of steam flow in the reservoir. It was observed that the rate of heat losses to the adjacent formations varies at each point the reservoir.

IV. Discussion

The foregoing observations have revealed that the rate of heat losses to the adjacent strata depends on a number of parameters. Each of these parameters can effect a significant change that could improve or reduce the rate of heat losses. At the same time, it has also been observed that certain properties, either or the formation or injection fluid, have no effect on the heat loss rate. Thus, such properties are said to be constant. The solutions revealed that these parameters must be considered when designing a prospective steamflood project.

V. Conclusion

For the conditions under which the numerical model for predicting heat losses from a tar sand formation into adjacent strata during steam injection operations, it was discovered that the rate of heat loss depended on a number of parameters – the nature and properties of the injection fluid and the reservoir. Thus, having an accurate data of the heavy or extra-heavy oil formation is very critical. It is the first step that would determine the feasibility of the thermal recovery technique. Additionally, such data would enable the project designer to formulate the best condition of the heat-carrying medium. Sensitivity analyses have revealed that the rate of heat loss to the cap base rocks could be reduced if the right properties, especially that of the injection fluid, are maneuvered. Consequently, the oil recovery rate would become economical when compared to capital and operating expenditures. However, it must be recognized that models are rough predictions subject to errors, thus they should be applied in conjunction with the experience of the operator.

What has been presented in this paper is only a simplified and provisional mathematical model for predicting heat losses from a linear formation to the adjacent strata. However, a rather complex phenomenon is embodied in a circular formation. Although some studies have been done in this area, more research would be needed to model heat losses in a radial formation. Furthermore, studies of the heterogeneity of the formation should affect the heat loss rate to be done.

VI. Nomenclature

A = area, m^2 (ft^2)
B = as defined in the text
c = specific heat capacity, Btu/lb-^{o}F
$d\dot{Q}$ = rate of heat from a segment of a pipe length dl to the adjacent formation, Btu/D
h = thickness, m (ft)
k = thermal conductivity
K_h = convective heat transfer coefficient, Btu/hr.ft^2.^{o}F (W/m^2.^{o}C)
m = mass, kg (lb)
Q = cumulative heat loss/consumption, kJ (Btu)
$\dot{Q}$ = rate of heat loss/ consumption, kJ/d (Btu/D)
ΔT = temperature difference between steam temperature and original reservoir temperature, ^{o}C (^{o}F)
T = temperature, ^{o}C (^{o}F)
U = overall heat transfer coefficient, Btu/hr.ft^2.^{o}F (W/m^2.^{o}C)
x = distance, m (ft)
t = time

6.1 Subscripts

F = fluid
h = hole
o, i = initial conditions
l, losses = heat loss zones overlying or underlying the steam zones
R = rock.

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APPENDIX

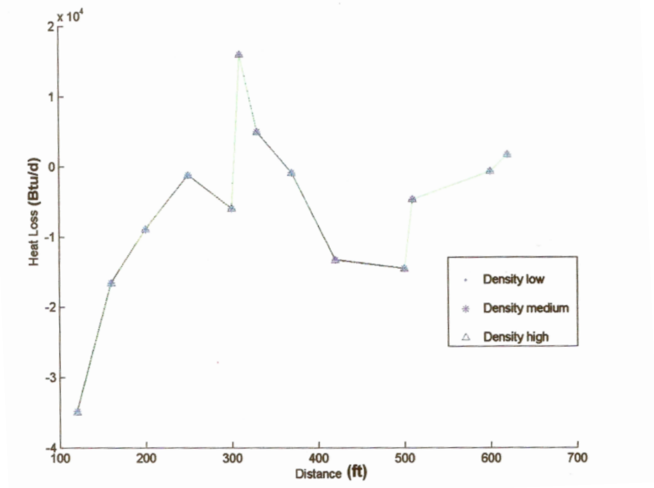

Figure 2: Sensitivity Plot of Density on Heat Loss

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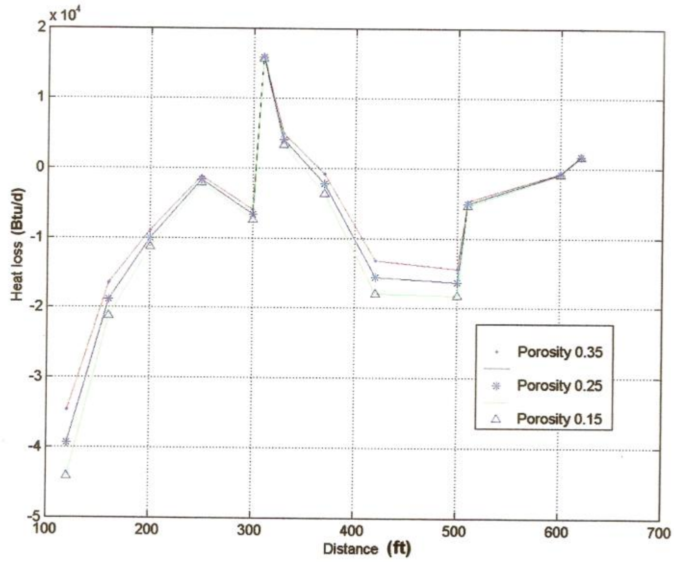


Figure 3: Sensitivity Plot of Porosity on Heat Loss

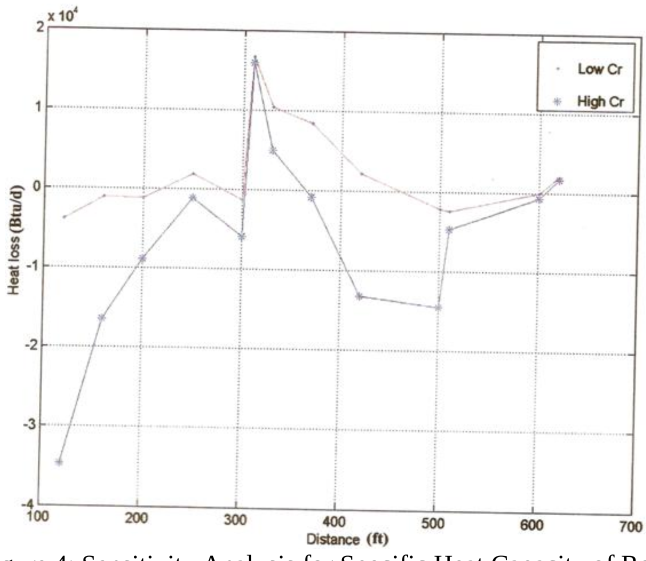
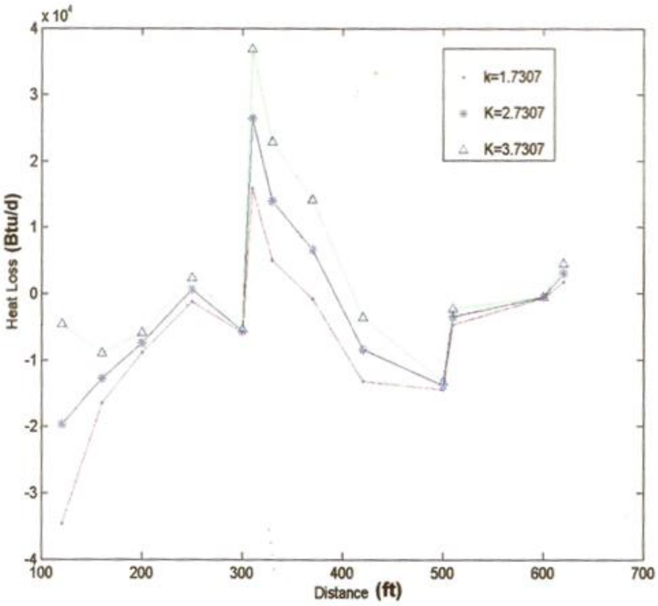


Figure 4: Sensitivity Analysis for Specific Heat Capacity of Rock



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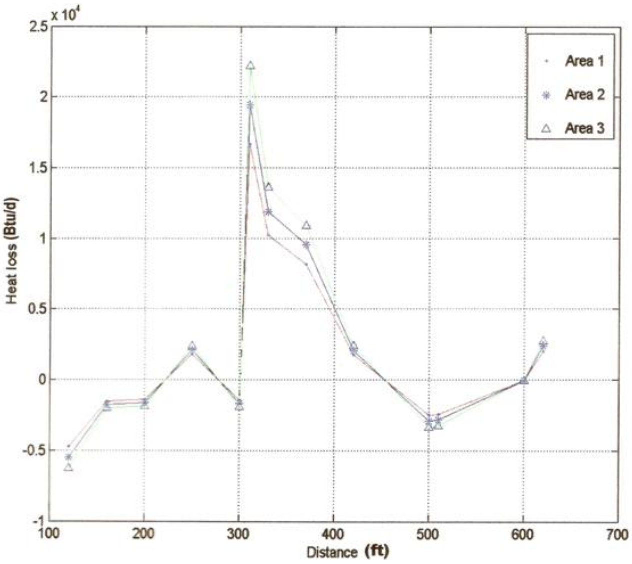

Figure 6: Sensitivity plot of heat loss against area change

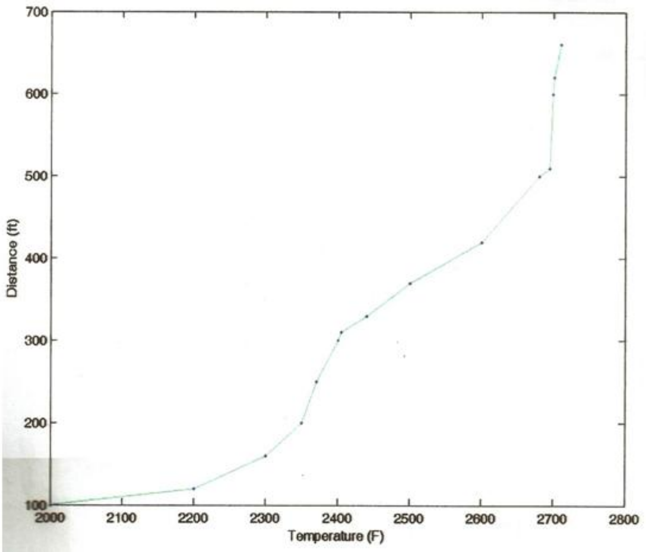

Figure 7: Sensitivity plot of distance against temperature

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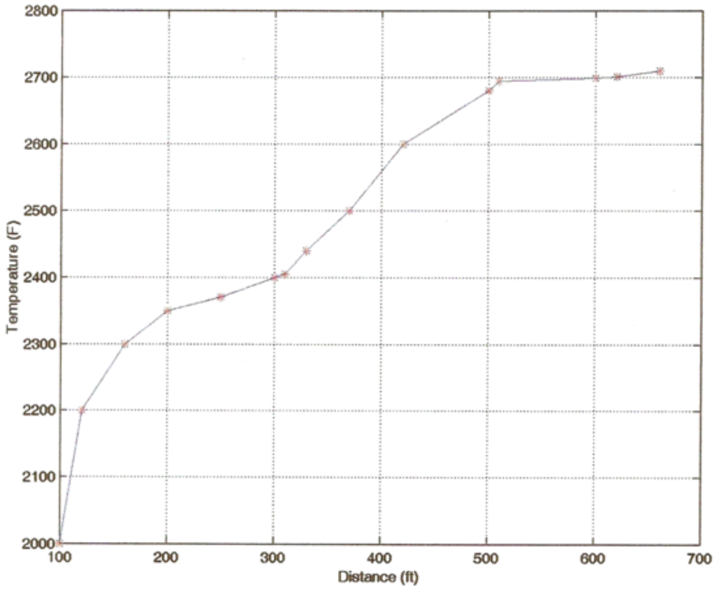

Figure 8: Sensitivity plot of temperature on distance

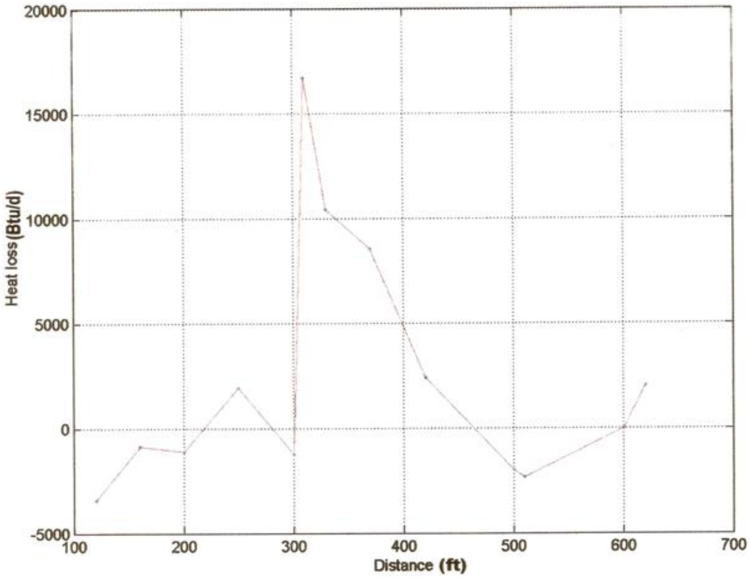

Figure 9: Sensitivity of heat loss against distance