STEAMING HEAT COILS FOR HEATING UP MARINE HEAVY FUEL OIL

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Abstract. *Usually ships use water heating coils for heating up marine heavy fuel oil in order to feed their engines. In the present work, the heat transfer from superheated water considered at high temperature (*151^{o}C*) and fixed pressure (5bar) to fuel oil tanks of specific dimensions was theoretically investigated. The heat transfer problem was formulated and numerically solved in meso-scale approach, by using commercial CFD software. Furthermore, thermodynamic analysis for the processes that take place in feeding ships was also performed. As far as the scope of this study was to estimate the size and needed length of the needed heating coil under the assumption of insulated tank, a parametric analysis was also performed in order to finally evaluate the most efficient tank's configuration.*

1 INTRODUCTION

Numerous merchant ships use nowadays slow-speed diesel engines that are fueled by the relatively inexpensive HFO (Heavy Fuel Oil). Such a tendency seems to will be still continued for many years. The efficiency of these large slow-speed marine diesel engines reaches today 48 - 51 % while a huge amount of heat is wasted, mainly through the flue gases [1]. For the HFO to be prepared for propulsion, i.e. to lower its viscosity to allow for better flow, a large amount of heat is necessary to increase its temperature, where superheated water is frequently used [2]. This concept of heat transfer between a heated liquid flux and a colder volume of stationary HFO is mainly encountered in applications other than ships' supply, such as oil drainage [3], recovery in wellbores [4], etc. As far as the amount of the necessary heat is quite huge, an efficient energy waste management is absolutely crucial.

Computational fluid dynamics (CFD) could be a very helpful tool towards this aim. It is actually the use of computer-based simulation to analyze complex systems involving fluid flow, heat transfer and associated phenomena such as chemical reactions, using mathematical models. The development and application of CFD have recently increased and become a powerful tool in the design and analysis stages of several engineering and industrial systems and processes [5, 6]. On the other hand, heat transfer process could be sufficiently described through normal thermodynamic analysis, at least from macroscopic point of view.

The main scope of the present work is to identify the appropriate geometrical characteristics and the length of the carbon-steel tube (coil) through which the superheated water flows and exchanges heat with the HFO. This application has been studied here from both thermodynamical and process-simulation points of view. Therefore, a standard thermodynamic analysis for heat exchange has been integrated, based on heat balances throughout control volumes. On the other hand, detailed simulations were also carried out, allowing for a deep understanding of the heat transfer process. The results of both approaches have been evaluated against geometrical characteristics (coil length, diameter, etc) and operational parameters (tank insulation, steam pressure).

2 THE SYSTEM

Consider a tank, with dimensions 3.2m X 7.6m X 12.56m and volume 306m^3, filled up to 85% with heavy fuel oil. This settling tank receives the HFO from ashore sources at average temperature 30^{o}C and has to heat it up to an average temperature of 60^{o}C. Towards this aim, heating coils are used, where the provided superheated water is at temperature 151^{o}C degrees at 5bar constant pressure. The coils are manufactured by boiler tube carbon-steel of 50mm external diameter with thickness 4mm, having a “serpentine” shape, as Figure 1 depicts. The main scope of the present study is to investigate the appropriate size and the length of the heating coil over specific time periods.

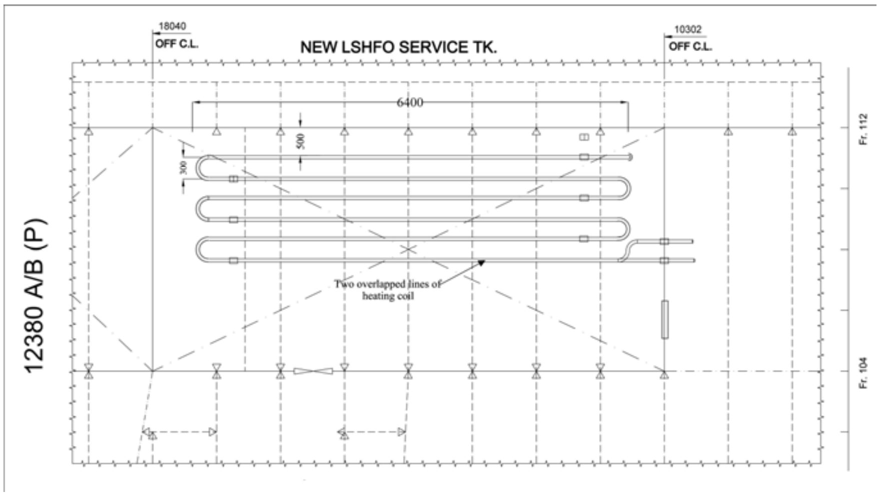

Figure 1. Heating steam coils.

3 THERMODYNAMICS OF HEATING

The thermodynamics of such a system are usually based on the energy (heat) balance between the heating fluid and the heated one, namely between superheated water and HFO. As far as the only heat source is the heated steam and by considering the total insulation of the apparatus, the above balance is as follows

$$Q_{superheated\ water} = Q_{oil} \tag{1}$$

The total amount of thermal energy supplied to the tank, Q_{oil}, can be written as [7]:

$$Q_{oil} = m\left[H_{fin}(T_{fin}) - H_0(T_0) \right] \tag{2}$$

where m is the total mass of the fuel oil (kg) calculated for a given tank volume through the temperature dependent density of the heavy oil [8]:

$$\rho = \frac{C_1}{C_2^{\left\{1+\left[1-\frac{T}{C_3}\right]^{C_4}\right\}}} \tag{3}$$

where $C_1 = 0.5373$, $C_2 = 0.2612$, $C_3 = 568.7$, $C_4 = 0.2803$ are coefficients, T is the temperature (K) and ρ is the density (kmol m^{-3}). Given the volume of the tank as well as the filling level, the initial total mass of heavy oil is 180509kg at $T = 303.15$K.

In the above Eq. (2), H_{fin} and T_{fin} is the enthalpy (J) and the temperature (K), respectively, at the final stage of the heating process and H_0 and T_0 are the same quantities at the initial step. The enthalpy for each chemical substance can be expressed through NASA polynomial as [9]:

$$\frac{H}{RT} = A_1 + \frac{A_2}{2}T + \frac{A_3}{3}T^2 + \frac{A_4}{4}T^3 + \frac{A_5}{5}T^4 + \frac{A_6}{T} \tag{4}$$

where R is the gas constant value 8.3144621 (J mol^{-1} K^{-1}), H is the enthalpy (J mol^{-1}) and A_1 up to A_6 are coefficients, specific for each chemical substance. For the HFO, these coefficients are [9]: A_1 = 1.25E+01, A_2 = -1.01E-02, A_3 = 2.22E-04, A_4 = -2.85E-07, A_5 = 1.12E-10 and A_6 = -2.98E+04.

The heat transfer takes place between the carbon-steel coil and HFO and can be described through the integral form of the Fourier's law [10]:

$$\frac{dQ}{dt} = -k\int_{\mathbf{A}} \nabla T dA \tag{5}$$

where $\frac{dQ}{dt}$ is the amount of heat transferred per unit time (J sec^{-1}), k is the thermal conductivity of the carbon steel (W m^{-1} K^{-1}), ∇T is the temperature gradient over the radial dimension of the system and the integral is closed over a the specific surface A of the cylindrical hot coil through which the heat transfer occurs.

By considering the above the geometry Equation 5 can be written as [11]:

$$\frac{dQ}{dt} = -\frac{2\pi L\, k\, \left(T_{out} - T_{in}\right)}{\ln\left(\frac{R_{out}}{R_{in}}\right)} \tag{6}$$

where L is the needed length of the coil, T_{out} and T_{in} is the temperature over the outer and inner cylindrical cell, respectively, and R_{out} and R_{in} is the outer and inner radius of the coil (thickness). Finally, the coil's needed length is given as:

$$L = \frac{Q_{oil}}{\frac{dQ}{dt}t} \tag{7}$$

where t is the time when the transfer process occurs (h).

4 HEAT TRANSFER IN DETAIL

The fundamental transport phenomena occurring in the system under consideration is the superheated water flow and the heat transfer from the coil to the oil. Since laminar conditions are considered, the flow can be well described by the Navier-Stokes equations, which for incompressible fluids are given as:

$$\frac{\partial(\underline{u})}{\partial t} + (\underline{u}\cdot\nabla)\underline{u} = -\frac{1}{\rho}\nabla p + \nu\left(\nabla^2 \cdot \underline{u}\right) \tag{8}$$

where $\underline{u}$ is the velocity vector, ρ the density, p the pressure and ν the kinematic viscosity. The above equation has to be considered along with the continuity equation:

$$\frac{\partial p}{\partial t} + \nabla\cdot(\rho\underline{u}) = 0 \tag{9}$$

By neglecting radiation, the energy balance in the system can be written as:

$$\frac{\partial}{\partial t}\left(\rho h\right)+\nabla\cdot\left(\rho \underline{u} h\right)=\nabla\cdot\left(k_{eff}\nabla T\right)+\frac{\partial p}{\partial t} \tag{10}$$

where T is the temperature, k_{eff} is the thermal conductivity and h is the total enthalpy of the fluid, given as:

$$h=i+\frac{p}{\rho}+\left\|\underline{u}\right\|^{2} \tag{11}$$

where i is the internal energy as a function of the state variables ρ and T.

Regarding the boundary conditions, the flow rate in the steam coil were assumed to be equal to 0.004m/s and, while pressure of 4.66E-5atm (4.72N/m^2) was set at the inlet and 3.65E-8atm (0.003N/m^2) at the outlet. Considering isothermal condition, zero heat fluxes were set at all the boundaries. Finally, non-slip condition was assumed for the steam flow inside the tube.

The above transient equations were considered strongly coupled, thus numerical solutions were obtained by the commercial CFD-ACE$^+$ package, based on the finite volume method, in order to achieve residual values less than 10^{-4}, for all calculated quantities. The three dimensional tank with the coil was discretized in space by structured grid consisting of approx. 80000 cells. The values of the parameters used as well as the properties of the materials are listed in Table 1.

12]

	SUPERHEATED WATER	HEAVY FUEL OIL	CARBON-STEEL
Phase	Liquid	Liquid	Solid
Density (kg m^{-3})	917.07	695.23	-
Viscosity (kg m^{-1} s^{-1})	0.0000182	0.000562 (for T=303K)	
Specific Heat C_p (J kg^{-1} K^{-1})	4290	NASA polynomials (2360 for T=303K) [9]	-
Thermal Conductivity (W m^{-1} K^{-1})	0.6821	NASA polynomials [9]	36

Table 1 : Parameters and properties used [12]

5 RESULTS AND DISCUSSION

5.1 Thermodynamics

The next Figure 2 clarifies the influence of the time on the coil's length. As expected, the shorter the time when heat transfer occurs, the longer the coil in order to assure the appropriate surface of the coil. This behavior is not linear since the amounts of heat that must be transferred to the oil are not linear with the time, as well. In particular, the heat transfer substantially occurs in two dimensions (cylindrical coordinates: r, θ) where the radial component is the only important, developing on several imaginary coaxial isothermal cylindrical surfaces through the total mass of HFO in the banker tank. For long time periods, the temperature of the oil increases in such a level that gradient is low enough for considerable heat fluxes. Furthermore, given a constant thickness of the steel tube (here is 4mm), the diameter is favorable parameter for the heat transfer, i.e. larger diameters assure higher available surfaces for heat transfer. It is important to underline the restrictions on the coil's length, imposed by tank's dimensions: the area covered by the coil's serpentine would not exceed 95.46m^2, which correspond to a maximum length of approx. 154m, depended on frame space (see Figure 1).

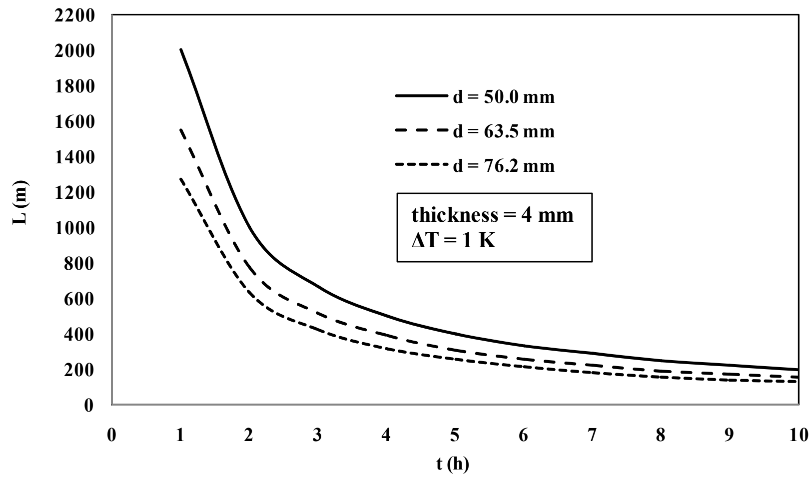

Figure 2. Coil's length as function of time

The importance of the geometrical characteristics of the coil is further depicted in Figure 3, where the same behavior of necessary length with the time is also observed. What is important here is that the length increases with the thickness for a given constant diameter (here is 50mm) because of the consequent increment of the heat capacity of the steam coil: by increasing the thickness, the steel mass is also increased and so does the amount of energy that is wasted to heat steel, as well. By ΔT in the above Figures is denoted the temperature difference between the inner and the outer (in contact with HFO) surface of the steam coil.

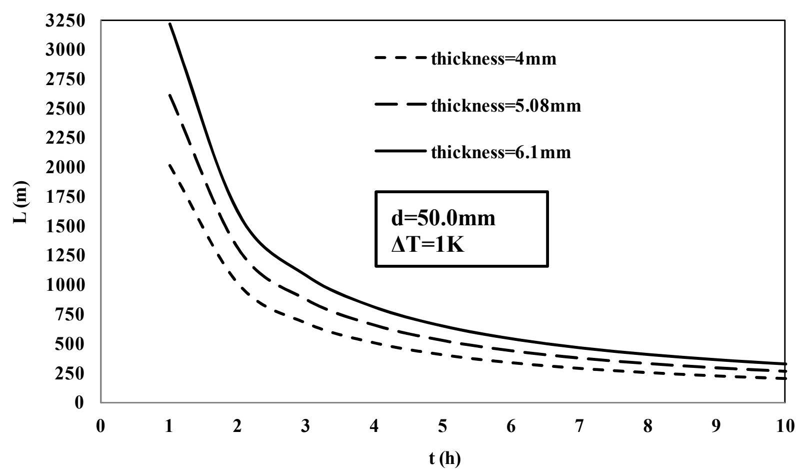

Figure 3. Effect of coil's thickness on its length.

The following Figure 4 further investigates the effect of this parameter on heat transfer, where it has been considered that the inlet temperature is 151.8^{o}C or 424.95K (superheated water). It is found that the necessary length is lower for higher temperature differences, because the latter corresponds to higher amounts of heat that are actually transferred to the heavy oil in the tank.

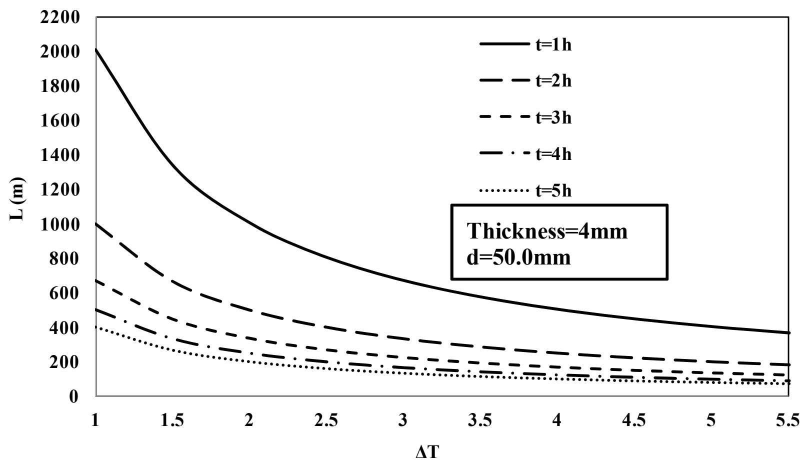

Figure 4. Length as a function of ΔT.

5.2 Detailed simulations

Typical temperature spatial distribution is presented in Figure 5 for two perpendicular 2-D cuts of the tank. The coil length is 160m and the time passed is 8h which consists the maximum sufficient time for the finalization of the heating process. The black line indicates the level of the heavy oil. It is shown that the majority of the volume occupied by heavy oil is indeed heated to 60°C. Areas of lower temperature are attributed to isothermal conditions (T = 30°C), assumed the walls of the tank.

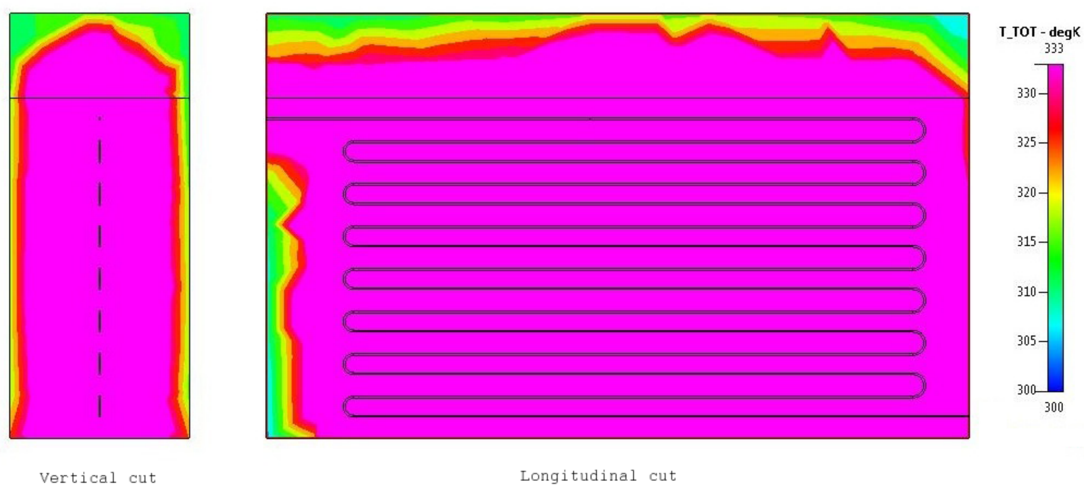

Figure 5. Typical microscopic results.

In order to quantify oil heating process, oil temperature has been spatially averaged and next presented in Figure 6 for various coils lengths. These microscopic results indicate that the tank reaches the desirable temperature of 60°C in a time period which exceeds the 8 hours time limit, for the shortest coil (=120m). Considering longer coils the time period can been calculated to approx. between 5 and 8h, a result that is in agreement with thermodynamic analysis. Insignificant discrepancies on the overall coil length and the estimated heating time process can be attributed to the average procedure (numerical errors) as well as to the boundary conditions imposed on the outer walls of the tank: for the energy balance established when the problem has been thermodynamically treated, the temperature of the tank has been assumed uniform while the outer walls were considered of temperature equal to the inner volume. The microscopic approach allows for a more detailed calculation of the temperature profile, thus some areas of significantly lower temperature can be recognized in the tank's volume. The time intervals of Figure 6 would be drastically larger if the requirement was that T ≥ 60°C in any internal point of the tank. Furthermore, these results are consistent with those of Figures 2 & 3: the longer the coil, the shorter the time needed for the oil to reach the desirable temperature of 60°C.

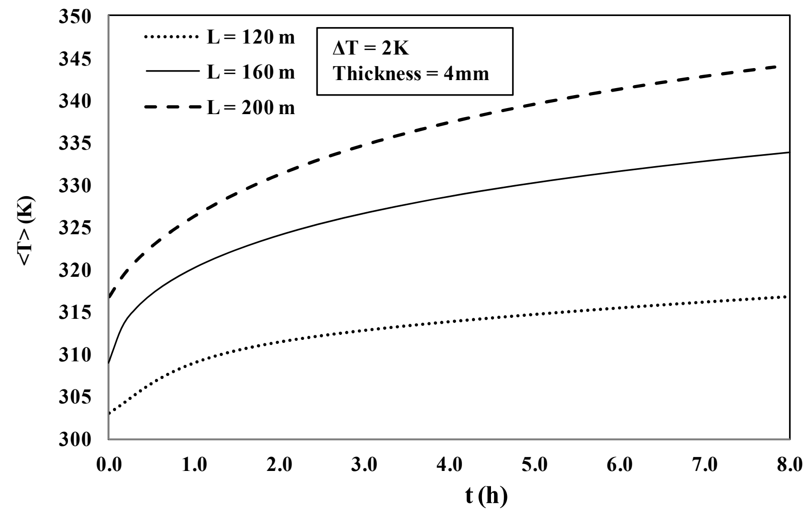

Figure 6. Average temperature as a function of time for various coil's lengths.

The effects of the geometrical characteristics of the coil are shown in the following figures. More precisely, Figure 7 presents the influence of coil's diameter on the time that tank reaches 60ºC on average. It is shown that the larger the tube, the shorter the time needed for attained the specific temperature, as also observed during the thermodynamical analysis (see Figure 2).

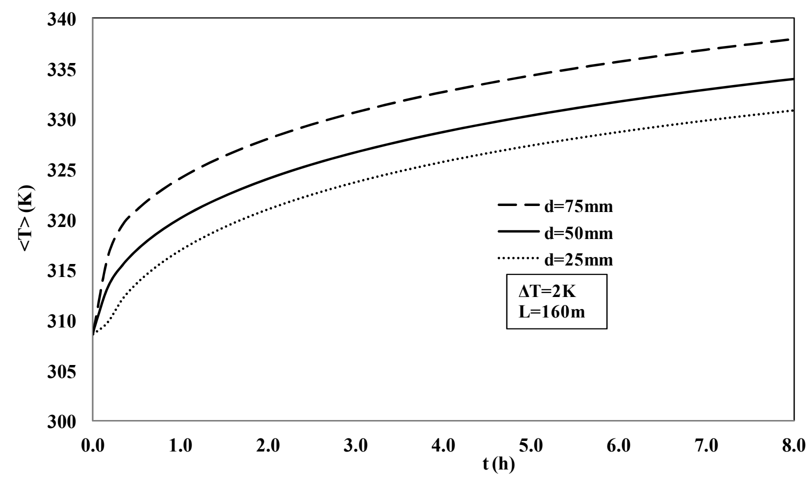

Figure 7. Effect of coil's diameter on <T>.

6 CONCLUSIONS

The heat transfer problem when a tank of specific dimensions is filled at about 85% with HFO is heated from 30ºC to 60ºC by exploiting the flow of superheated water trough a coil of serpentine design and of various lengths, diameters and thicknesses. To obtain length values, both a thermodynamical analysis as well as detailed 3-D simulations have been carried out, while the effect of the most crucial parameters on the results was investigated. It is found that the appropriate length is approx. 154m – 300m for feasible short time periods that the process takes place. More specifically, the maximum length which can be established due to the limitations on geometrical characteristics of the banker tank cannot exceed 154 m for one layer of carbon-steel coil of 50mm diameter and 4mm thickness and this can increase the HFO temperature to 60ºC in about 7.5h through thermodynamic analysis and 8h through 3-D CFD-ASE$^+$ simulations which constitutes the most favorable result for the feeding process to the engines.

The most efficient scenario can be presented through the installation of a double layer of carbon-steel coil which increase the overall length at about 300m and the needed time can be limited at an interval of 4 hours. The main disadvantages for such an established scenario can be observed on the homogeneity of the temperature of the total HFO and on the increased initial establishment costs for this construction. Finally, it has to be mentioned that the temperature of the HFO inside the banker tank found hardly uniform, for lower time interval processes, due to stirring physically occurs during the oil's entering in the tank and due to the variation of its viscosity among the several time steps.

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