Modelling of LNG Vaporisers

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Abstract

The objective of this project has been to develop a program that models the performance of an ambient LNG vaporiser for KHG. The vaporisers are not operating as required by design specifications. The pressure drop across the vaporisers is greater than the design parameters for a given flow rate. In the winter months the vaporisers frost over, reducing their capacity.

This program has been written in MATLAB. The model will consider conduction, free convection, frost formation, fin shapes, internal flow, and boiling. The theories, laws and equations of thermodynamics/heat transfer are well established; therefore the project has involved researching the previous topics in a literature review. As all properties are transient, the model uses an iterative process to perform calculations. Results achieved to date are as expected and will later be validated by measurements taken from site.

The program will be a tool for KHG to increase their understanding of the vaporiser performance. It may be used to alert them to conditions that will reduce the desired flow rate and allow them to make informed design decisions.

1. Introduction

Wesfarmers Kleenheat Gas (KHG) use atmospheric vaporisers to convert Liquefied Natural Gas (LNG) from liquid in storage to gas for combustion. A significant amount of energy is required for the large change in temperature, the latent heat and superheating of the LNG. This energy is transferred from the atmosphere to the LNG by finned tube heat exchangers. The heat is transferred through internal forced convection, conduction, and free convection. Due to the low heat transfer coefficient from free convection, a large surface area is required (Bernert et al. 1993).

The performance of LNG vaporisers can be measured by two parameters, outlet temperature and pressure. KHG have highlighted the benefit in creating a program that can model the performance and predict a given vaporisers capacity. The capacity of a vaporiser may be limited by an excessive pressure drop or low thermal performance.

The cryogenic temperature of the vaporisers causes the water vapour in the air to condense and freeze on the external surfaces. The low conductivity of the frost reduces the total heat transfer coefficient of the vaporisers. The total heat transfer coefficient will continue to drop as the frost increases in thickness and covers the length of the vaporiser. During the winter months the vaporisers have a tendency to completely frost over, due to the low atmospheric temperature and high relative humidity. For this reason vaporisers are installed in pairs and run for a given duty cycle. This allows one vaporiser to "defrost" while the other is in operation.

Once the gas leaves the vaporiser it may enter carbon steel pipes. If the outlet temperature drops too low, the risk is deemed too great to have low temperature gas flowing through carbon steel pipes. Many BCC structure materials such as Carbon Steel have a transition temperature at which the ductility and toughness are significantly reduced (Callister WD 1997). The carbon steel pipes from the vaporiser would become susceptible to fatigue from vibration, or fracture from an impact at low temperatures. The consequences of a failure could be disastrous and should be avoided at all costs.

During the warmer seasons in Australia the thermal performance of the vaporiser is not a problem. The larger temperature difference increases the rate of heat transfer. However, another limiting performance condition is the pressure drop across the vaporisers. For high flowrates the drop in pressure could be too large. If the gas is being used for power, the power output will be reduced causing other problems. In the industrial world this has potential to be expensive and embarrassing.

The purpose of this project has been to develop a program that models the performance of the vaporiser. Building a model should create a better understanding and a tool to be used in design decisions for KHG. Options such as adding fans that increase airflow have not been directly considered, but the model will create an understanding of what conditions affect the performance and by how much. The model will predict the duty cycle of the vaporisers, for a given size and flow rate. It will allow KHG to predict the required size and arrangement of a vaporiser for a given flow rate and pressure. The model will show the limits of the existing vaporisers. This will allow KHG to make informed decisions when installing or modifying vaporisers.

2. Model Formulation

The model has been created using the program MATLAB. The model is written in an M-file and uses the basic features of MATLAB to loop calculations, store arrays, and graph results. There are minimal inputs required from the user and the program will prompt the user when they are required.

2.1 Thermal Circuit

One way of solving the thermal performance of the vaporiser is by setting up a thermal circuit diagram. The rate of heat transfer is proportional to the surface area of a substance and the temperature difference. This relationship is known as Fourier's Law.

$$\dot{q} = k\frac{dT}{dx} \quad \text{Fourier's Law (conduction)}$$

$$I = \frac{V}{R} \quad \text{Ohm's Law}$$

Fourier's Law is similar to Ohm's Law, where the temperature difference and voltage are equivalent, heat flow and current, and lastly thermal conductivity per unit thickness being equivalent to resistance. This similarity makes it useful to solve the problem using a thermal circuit and calculating the thermal resistances. This can be seen in Figure 1.

The heat transfer rate (q) is calculated by dividing the temperature difference (dT) by the total thermal resistance (R_t). This resistance is the sum of all resistances, forced convection to the LNG and free convection to the air, conduction through the extrusion, resistance through fins, and the resistance through the frost that forms on the cryogenic surface (Figure 1).

The resistance to convection is dependant on the surface area and the convection coefficient. The convection coefficient is dependant on the fluid velocity, flow type and various other parameters that are calculated. Two very important relationships in this calculation are the Nusselt number and Reynolds number. These are dimensionless numbers that describe the conductive to convective heat transfer and the flow regime respectively (Incropera 2007).

$$R_1 = \frac{1}{2\pi h_{LNG} r_{in} dz} \tag{1}$$

The conductive resistance through the round tube is calculated, using the thermal conductivity of the tube material and the size of the tube.

$$R_2 = \frac{\log(r_{out}/r_{in})}{2\pi k_{pipe} dz} \tag{2}$$

The resistance of the outer surface of the extrusion is a little more complicated due to the finned extrusion. Several formulas are used to calculate the fin efficiency based on the extra area and fin spacing.

Fin efficiency
$$\eta_f = \frac{\tanh mL_c}{mL_c} \tag{3}$$

Overall efficiency
$$\eta_o = 1 - \frac{NA_f}{A_t}\left(1 - \eta_f\right) \tag{4}$$

Overall resistance
$$R_3 = \frac{1}{\eta_o h A_t} \tag{5}$$

Finally the frost growth needs to be calculated. This stage has not been correctly developed into the model yet.

2.2 Transient Iteration

As the model moves down the length of the pipe the resistance changes. This is due to the changing ice thickness with length, making it difficult to model the overall resistance and heat transfer of the vaporiser. The only way to calculate the overall heat transfer is to break the vaporiser into small segments and calculate the heat lost from each segment. The sum of all heat transferred through each segment will give the overall heat transfer.

The transient nature of this problem, that is the changing frost thickness over time requires a second iteration. As a result the program has two loops; one for time and one for length.

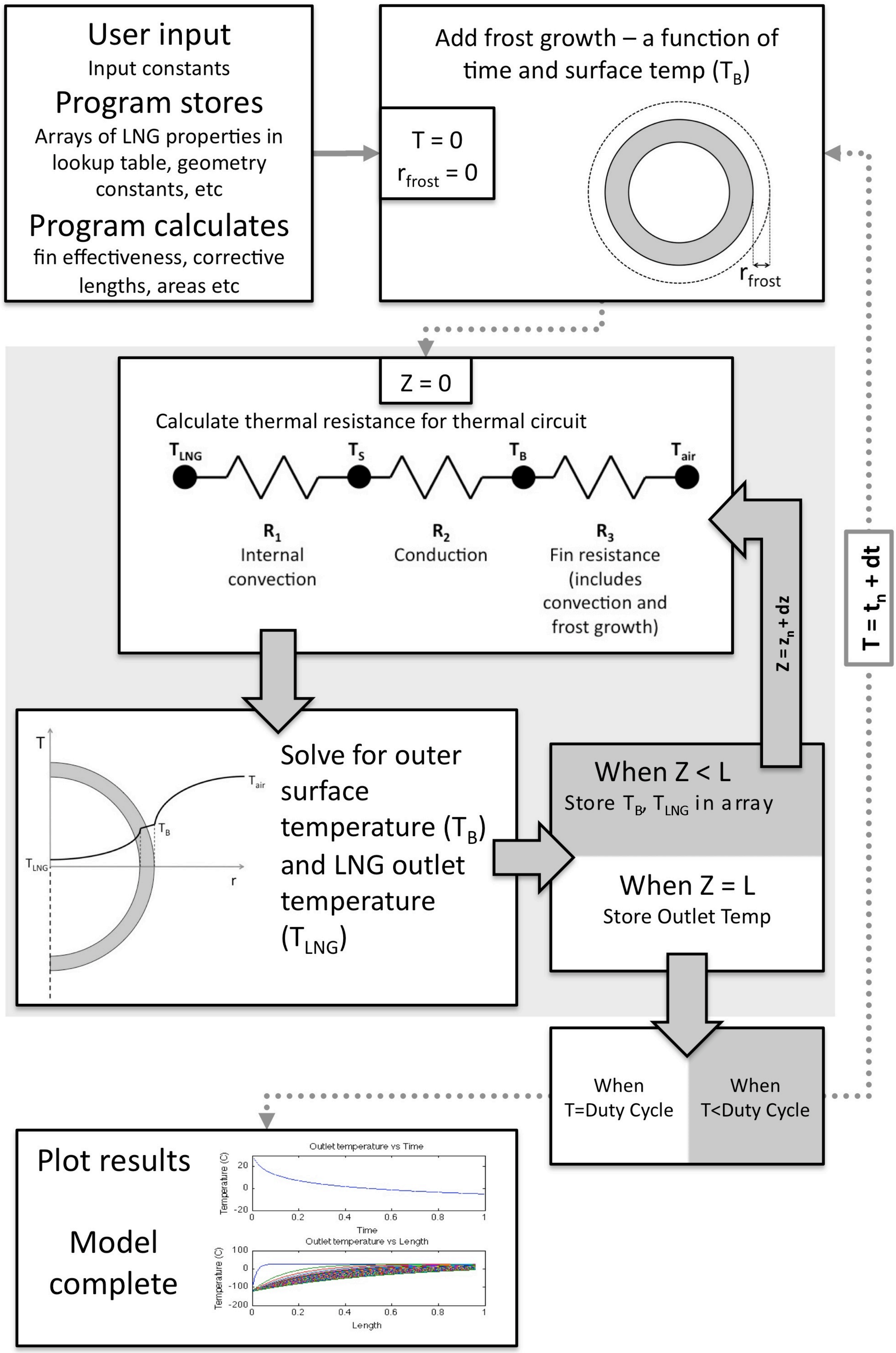

Figure 1 Schematic of the model's logic.

3. Results and Discussion

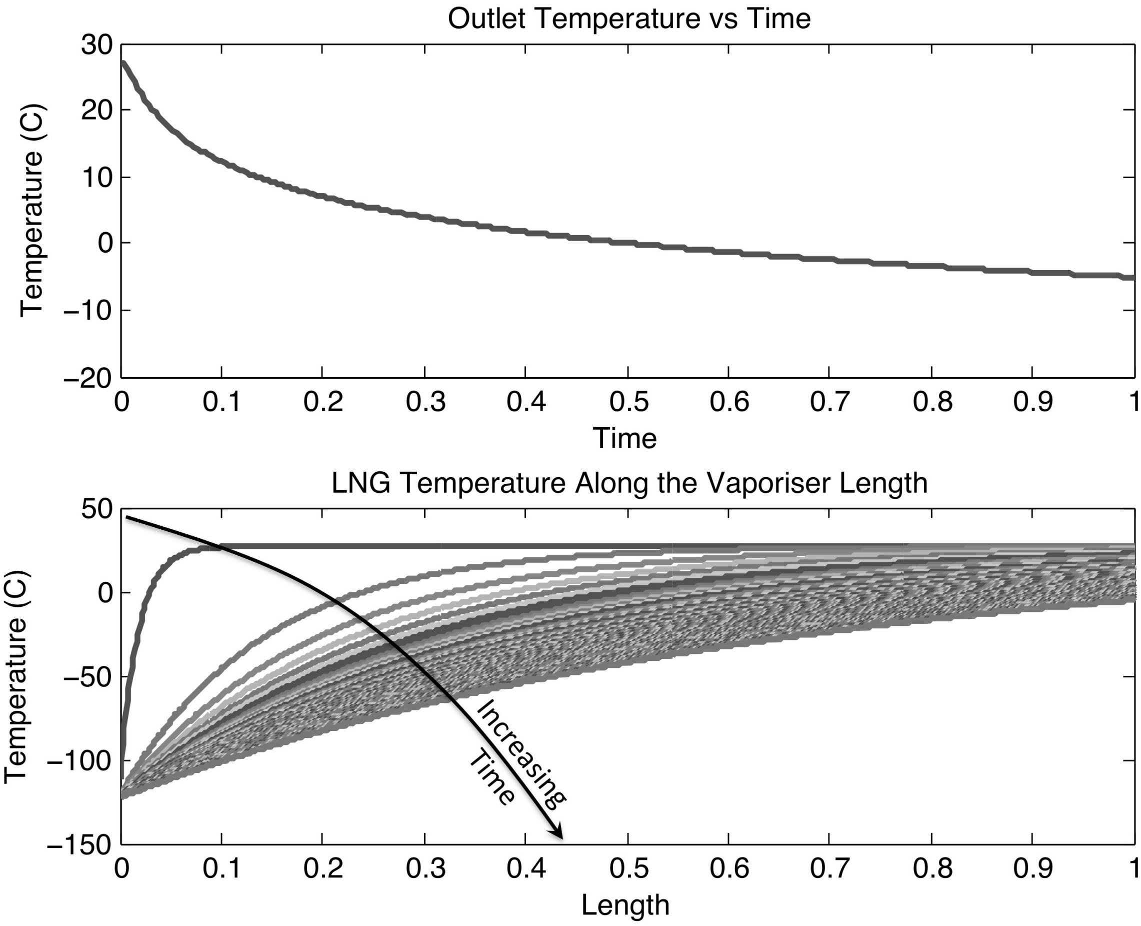

Figure 2 Non-dimensionalised plots of LNG temperature with time and length.

The results shown in Figure 2 are non-dimensionalised for confidentiality reasons. The first plot shows the outlet temperature decreasing over the duty cycle. The second plot provides more detail, as it displays the temperature of the LNG along the length of the vaporiser. There is a separate line for each step in time. The shapes of both plots are similar to what is expected. As length increases the LNG temperature increases and as time increases the LNG temperature decreases. The vaporisers become less effective as time increases due to the insulation from frost formation. The graphs will improve when a proper frost formation model is written in the M-file. A method for determining a rate of frost growth and corresponding changing surface area is currently being added into the model.

Results from the literature review have concluded that currently there is no generic rule, equation, or model, that is respected as the best way of modelling frost formation. A method will be chosen that calculates the growth based on surface temperature, humidity, and air temperature, as these parameters are readily available.

4. Conclusions and Future Work

4.1 Conclusions

The M-file is still in progress, but will be finished by the end of the thesis. The file still needs to incorporate a true pressure drop and a frost formation model. The output of the M-file will also include pressure graphs versus time and length. This output will make it possible for a user to view where the boiling region occurs. Once these extra steps are added the program should be validated using the outlet temperature data gathered from one of KHG's vaporiser sites.

4.2 Future Work

Further work could be done to justify all assumptions made within the M-file. Different averaging and iterative techniques could be used to determine if a more accurate result is reached.

It may be useful to validate the iterative technique without frost formation by comparing it to another technique such as the LMTD. Similar results will increase confidence in the model and eliminate a possible error source.

The program could later be revised to include new features. Many vaporisers operate with fans (forced convection) and it would be useful to model the performance of such cases.

5. References

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