

Boiling Heat Transfer

Baran Anil

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Laboratory Investigation 1A

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UNIVERSITY OF
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Abstract

The objective of this experiment is to analyze the performance of an industrial scale pre-heater, which shall be used in an incineration plant, after being assessed on a smaller scale in laboratory conditions. The main principles applied to this experiment are the various boiling regimes, which are: Convection, Nucleate, Transition and Film boiling in which the experiment displays all the different boiling regimes. The liquid temperature and the heat source temperatures will, also be taken to calculate the excess temperature (ΔT_{excess}). As well as this the critical heat flux (Q''_{crit}) and the maximum heat transfer coefficient ($h_{\text{fg, mass}}$) will also be identified. From the experiment, it was concluded that the Q''_{crit} was around 236 kW m^{-2} and the $h_{\text{fg, mass}}$ was around $\text{kW m}^{-2} \text{ K}^{-1}$. The increase in the temperature excess leading to the increase in the critical heat flux and the maximum heat transfer coefficient clearly and the fact that all the distinct boiling regimes being observed showed that the objective of the experiment was achieved.

Results and Calculations

The graphs for heat flux and the heat transfer coefficient were formed by taking the raw data for the power of the rig and divided by the area of the heating element, this gave values for the heat flux, the heat transfer coefficient graph was formed by taking the heat flux values and dividing them by the excess temperature, the graphs can be seen below:

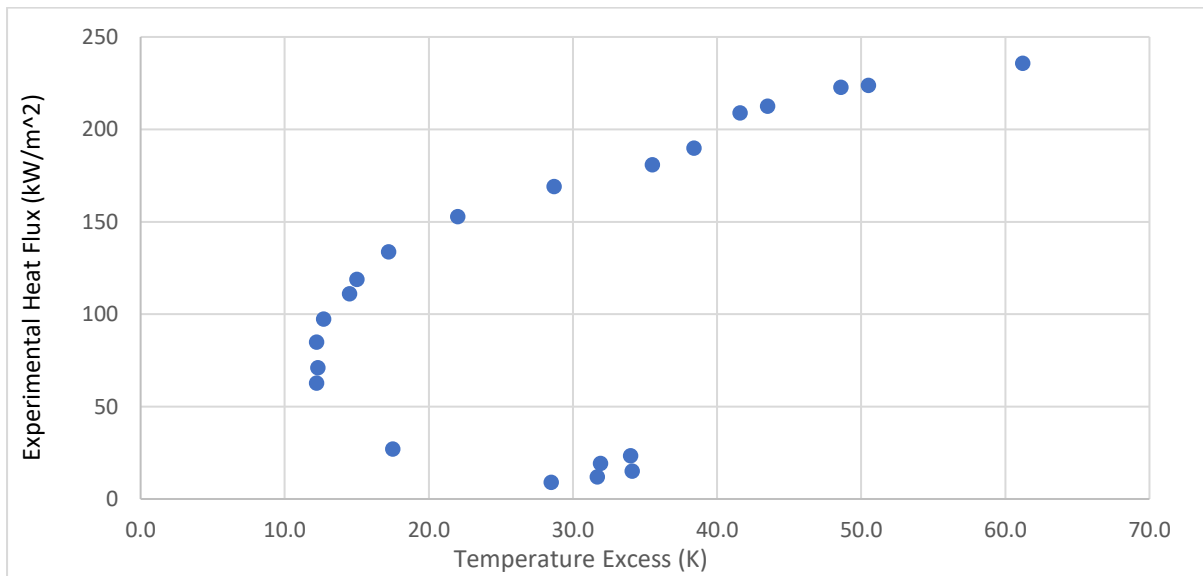


Figure 1: Graph of Experimental Heat flux against the Temperature Excess

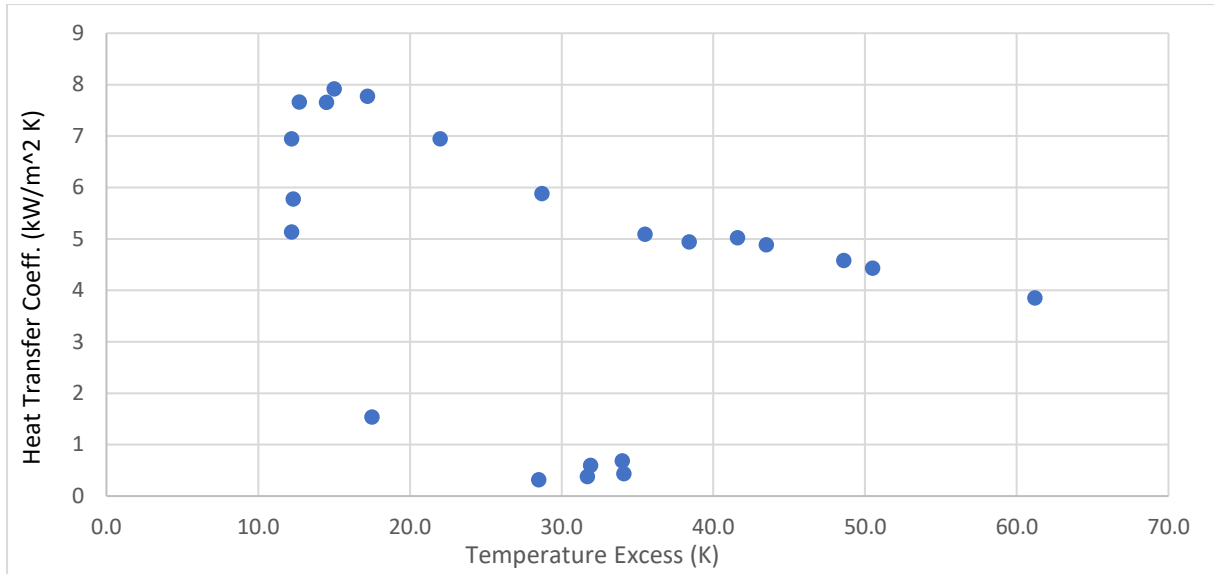


Figure 2: Graph of Heat Transfer Coefficient against the Temperature Excess

After an analysis of both Figure 1 and Figure 2, the conclusion was made that the Critical Heat flux was at around 236 kW/m² and the maximum heat transfer coefficient was at around 7.92 kW/(m² K), both these respective values are given at 3 significant figures.

The graphs were formed on an excel sheet using Equation 1 to convert the units from Watts to W/m², this was done by calculating the area of the surface of the source of heat via Equation 2 and divide the power values obtained experimentally by this area calculated.

Once these experimental values were obtained the next phase was to calculate the Theoretical Heat Flux. The way to do this was to first produce a graph of the liquid and vapour densities of the Pentafluorobutane. Once this graph was produced, a density was chosen at the saturation temperature for both liquid and vapour and the densities were inserted into Equation 1. The saturation temperature was assumed to be at RTP, room temperature and pressure, hence to corresponding density values were chosen from Figure 3, as displayed below:

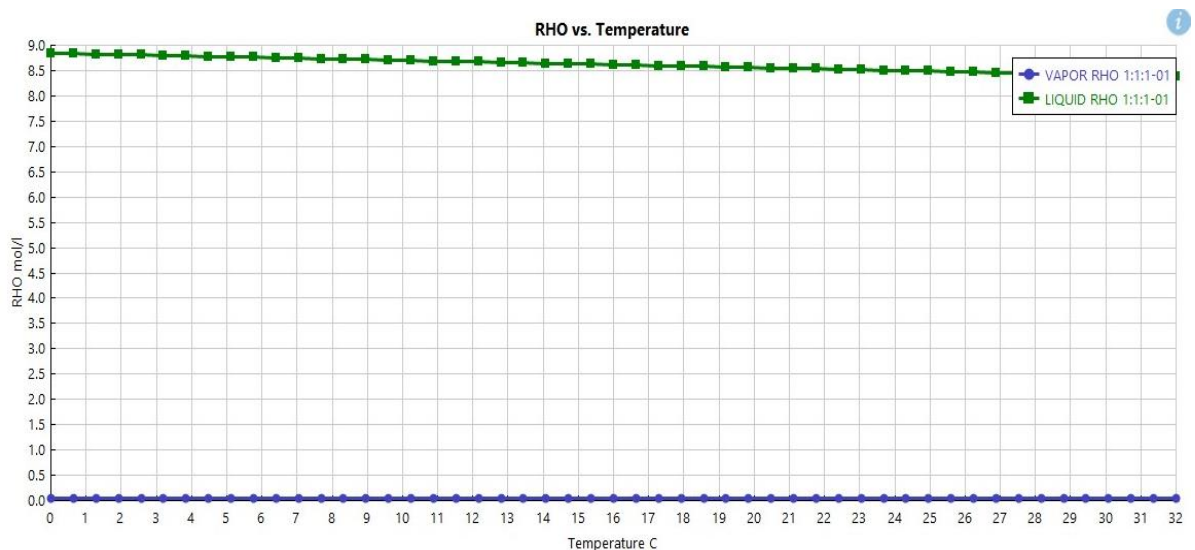


Figure 3: Density against Temperature Graph for the Liquid and Vapour phases of Pentafluorobutane

After plotting the graph for Density against temperature, the densities for the liquid (ρ_f) and vapour (ρ_g) phase for Pentafluorobutane is identified at 25°C, the corresponding values are:

$$\rho_f = 8.5 \text{ mol L}^{-1}, \rho_g = 0.0436 \text{ mol L}^{-1}$$

These then need to be converted to kg m^{-3} in order for the units to be consistent with the Zuber equation, Equation 7 and 8, calculations can be found in Appendix 1.3 and 1.4, respectively:

$$\rho_f = 1258 \text{ kg m}^{-3}, \rho_g = 6.453 \text{ kg m}^{-3}$$

As well as the densities of the Pentafluorobutane, other variables such as the surface tension (σ) and the latent heat of vapourisation (h_{fg}) is required, these could be found from various sources, where: $h_{fg} = 29.2 \text{ kJ/mol}$ (Marrucho et al., 2018) and $\sigma = 0.01565 \text{ N m}^{-1}$ (Klomfar, 2013). However, for the consistency of the units, the latent heat of vapourisation was converted to kJ/kg:

$$h_{fg, mass} = \frac{h_{fg, molar}}{M_r(\text{Pentafluorobutane})} \quad \text{Eq. 3}$$

$$\therefore h_{fg, mass} = \frac{29.2}{(148 \times 10^{-3})} = 197 \text{ kJ kg}^{-1} \text{ (to 3 s.f.)}$$

The next step was the calculation of the theoretical critical heat flux, U_{max} , via Equation 4, the Zuber equation (Zuber et al., 1961), below:

$$U_{max} = \left(\frac{\pi h_{fg} \rho_g}{24} \right) \left(\frac{g \sigma (\rho_f - \rho_g)}{\rho_g^2} \right)^{\frac{1}{4}} \left(\frac{\rho_f}{\rho_f + \rho_g} \right)^{\frac{1}{2}} \quad \text{Eq. 4}$$

$$U_{max} = \left(\frac{\pi \times 197 \times 6.453}{24} \right) \left(\frac{9.81 \times 0.01565 \times (1258 - 6.453)}{6.453^2} \right)^{\frac{1}{4}} \left(\frac{1258}{1258 + 6.453} \right)^{\frac{1}{2}}$$

$$\therefore U_{max} = 243.3 \text{ kW m}^{-2}$$

Once the maximum theoretical heat flux is calculated, this can be compared to the experimental flux value and the efficiency, η , of the source of heat can be calculated via Equation 5 below:

$$\eta = \frac{Q''_{crit}}{U_{max}} \quad \text{Eq. 5}$$

$$\therefore \eta = \frac{236}{243.3} = 0.970 \text{ (to 3 s.f.)}$$

The time taken to boil 175 kg of the CFC is calculated via Equation 6, if assumed that the heating rig operates at 80% of the experimental critical flux and that the area that heat transfer occurs is 0.032 m^2 :

$$t = \frac{(197 \text{ kJ kg}^{-1} \times 175 \text{ kg})}{(0.8 \times 236 \text{ kW m}^{-2}) \times 0.032} = 5706 \text{ s} = 95.1 \text{ minutes} \quad \text{Eq. 6}$$

Therefore it takes 95.1 mins or 1 hour and 35 mins to boil 175kg of CFC to 80% of its critical flux with the given area for heat transfer.

Conclusion

The main aim of this experiment was to analyze and identify the different boiling regimes visible within the heating rig. As the power of the rig was gradually increased, the shift of the boiling regimes from convection to nucleate to transition and film boiling could be visible to some degree. As the power of the rig was increased, the temperature also increased proportionally, which in return increased the temperature excess of the system.

Unfortunately, there were errors that affected the overall efficiency of the rig, the first one would be the high sensitivity of the dial to increase the power of the rig, The slightest turn would cause for big leaps between the power values as the turning of the dial would often cause for the power to overshoot and the desired increase in power was very inaccurate, often overshooting by 10 - 20W, leading to an inaccurate graph to find the experimental critical flux. The other major error was the difficulty in reading the surface temperature of the source of heat, this was due the increase in turbulence of the bubbles forming in the film boiling phase covering the classic thermometer in the solution, hence the reading was assumed towards the end, leading to an inaccurate value for the excess temperature, and affecting the overall graph in Figure 1.

These results would not be consistent when scaled up to an industrial level. This is because on a small scale, the effects of fouling are proportional, hence small but when scaled up to larger quantities, the effect of fouling on the efficiency of the rig or the system would be greater.

References

- Marrucho, I.M., Oliviera, N.S. and Dohrn, R., 2018. *Vapor-Phase Thermal Conductivity, Vapor Pressure, and Liquid Density of R365mfc* [Online]. Available from: <https://pubs.acs.org/doi/10.1021/je015534%2B> [Accessed 21 February 2022].
- Klomfar, J., 2013. *Surface Tension and p–ρ–T Data for 1,1,1,3,3-Pentafluorobutane (HFC-365mfc) and 1,1,1,2,2,3,3-Heptafluoro-3-methoxy-propane (HFE-347mcc)* [Online]. Available from: <https://pubs.acs.org/doi/10.1021/je4004542> [Accessed 21 February 2022].
- Zuber N, Tribius M, Westwater JW, (1961) The hydrodynamic crisis in pool boiling of saturated and sub-cooled liquids, Proc. Int. Heat Transfer Conf., Denver, Paper 27.

Appendix

$$1.1 \quad Q'' = \frac{Q'}{A_s} = \frac{Q'}{\pi d L} \quad \text{Eq.1}$$

$$1.2 \quad h = \frac{Q''}{\Delta T_{excess}} = \frac{Q''}{(T_{surface} - T_{fluid})} \quad \text{Eq.2}$$

$$1.3 \quad \rho_f = 8.5 \text{ mol } L^{-1} \times 148 \text{ g mol}^{-1} = 1258 \text{ g } L^{-1} = 1258 \text{ kg m}^{-3} \quad \text{Eq.7}$$

$$1.4 \quad \rho_g = 0.0463 \text{ mol } L^{-1} \times 148 \text{ g mol}^{-1} = 6.453 \text{ g } L^{-1} = 6.453 \text{ kg m}^{-3} \quad \text{Eq.8}$$