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Enhancement of Dropwise Condensation Heat Transfer of Steam by Oleic Acid

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ABSTRACT

Thisstudy compares the heat transfer coefficients for film and dropwise condensation of steam.Copper tube was coated with oleic acid to promote dropwise condensation of steam rather than a continuous film. Excellent dropwise condensation was observed when the cooling surface was coated with oleic acid, and this helps to enhance droplet formation without wetting the surface.The experimental results shows that the value of overall heat transfer coefficient is 50000 W/m^2K in dropwise and 12500W/m^2K in filmwise condensation.Thus, theoverall heat transfer coefficients during dropwise condensation are approximately four times greater than those during filmwise condensation at the same surface subcooling degrees.

Introduction

When the temperature of a surface in contact with a vapour is below saturation temperature, liquids condensate wet and spread out on the surface forming a stable film, this is called filmwise condensation. On the other hand, if the condensate does not wet the surface; instead forming droplets which run down the surface it is called dropwise condensation[1]. The film and dropwise condensation experiments are of great interest to the designers of commercial condensing equipments whose priority is higher heat transfer rate. Most of the condensers used in the real world applications are huge in size and are very expensive to manufacture or purchase. Any breakthrough made in enhancing the condensation heat transfer rate would greatly reduce the driving potential or reduced pumping power required for desired output and finally the possibility of cost and size reduction for the particular heat exchanger[2].

Dropwise condensation mode had not been widely applied to practical heat exchanger devices due to the crucial problem of finding effective promoters.This has prompted the interests of researchers in the field and inspired further investigation on the appropriate promoters of dropwise condensation. Dropwise condensation can be promoted by coating the condensation surfaces with a film of substance than cannot be wet by the liquid, examples of dropwise condensation promoters include fatty acids, waxes, thin layer of special metals such as gold, chromium and light hydrocarbon oils[3].

In this work, oleic acid was used to promote drop wise condensation of steam on copper tube rather than a continuous film on bare surface. The aim is to determine and compare the individual film heat transfer coefficient for film and drop wise condensation of steam at atmospheric pressure.

Nomenclature

Q	Heat flux (w/m^2)
Q^1	volumetric flow rate (m^3/s)
U	overall heat transfer coefficient (W/m^2K)
u	coolant velocity(m/s)
o.d	outside diameter of the tube (m)
i.n	inside diameter of the tube (m)
L	length of the tube (m)
t_i	inlet water temperature (^oC)
t_o	outlet water temperature (^oC)
t_s	steam (out) temperature (^oC)
ΔT	logarithmic mean temperature difference (K)
h_o	outside film heat transfer coefficient (W/m^2K)
h_i	inside heat transfer coefficient (W/m^2K)
m	mass flow rate of the coolant (kg/s)
A	circumferential area (m^2)
A_i	internal area (m^2)

Experimental Setup and Procedure

The schematic diagram of the experimental setup is shown in figure1. A doubled-tube (pipe) condenser was used in the heat transfer experiment. Cooling water was supplied at 100 gallons/h through the pipe. Steam was introduced into the first condensing chamber and condensed (filmwise condensation) on the cool pipe surface. This setup was left for 2-3 minutes to allow a steady state condition. The temperatures T1, T4, and T5 representing water in, water out and steam out respectively were recorded. The cooling water flow rate was then readjusted at decreasing values, for instance 90, 80, 70.........10 gallons/h to provide additional conditions for a range of data.

The pipe in second condensing chamber was coated with uniform layer of oleic acid and steam condensed (dropwise condensation) on the coated pipe surface. The same procedure used in filmwise condensation was repeated; the temperatures T1, T2, and T3 representing water in, water out and steam out respectively were recorded.

The heat flux (Q), overall heat transfer coefficient for condensation (U), and fluid velocity (u) were calculated as described in the data reduction below, graph of 1/U was plotted against $1/u^{0.8}$. The heat transfer coefficient ho was determined directly from the intercept[4].

Data reduction

Heat is transferred from steam by a combination of radiation and convection to the outer surface of the pipe, and then passes through the walls by conduction, finally to the cooling water in the pipe by convection. The heat transferred Q is proportional to the area available for the flow of heat (A) and the temperature driving force (ΔT).

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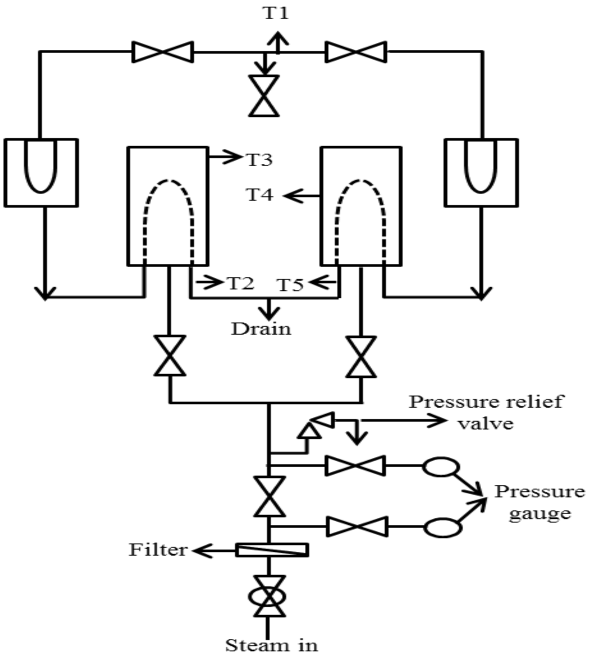

Figure 1: Schematic diagram of experiment set-up

The simplest form of equation which represents these forms of heat transfer is written as;

$$Q = UA\Delta T \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where U is the proportionality constant known as overall heat transfer coefficient (W/m^{2}K)

The experimental apparatus consist of a pipe through which cooling water flows. Steam condenses at atmospheric pressure on the outside.If the steam temperature t_s changes the cooling water temperature from the inlet temperature t_i to the outlet temperature t_o the temperature driving force is given by;

$$\Delta T = \frac{(t_s - t_i) - (t_s - t_o)}{\ln\left[\frac{t_s - t_i}{t_s - t_o}\right]} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2$$

The steam condenses on the outside of the tube, through which water is passed at various velocities. If the transfer area on each side of the tube is approximately the same then the overall and film transfer coefficients is given as;

$$\frac{1}{U} = \frac{1}{h_o} + \frac{x_w}{k_w} + R_i + \frac{1}{h_i} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

For conditions of turbulent flow the transfer coefficient for the water side $h_i = \alpha u^{0.8}$, where u is the fluid velocity, the scale resistance R_i is constant, the coefficient of the condensate film h_o is almost independent of the water velocity. K_w and x_w are the thermal conductivity and thickness of the wall (we assume that the wall resistance is negligible) equation (3) reduces to;

$$\frac{1}{U} = (constant) + \frac{1}{\alpha U^{0.8}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

A plot of 1/U against 1/u$^{0.8}$ gives a straight line with slope of 1/α and intercept equals to the value of the constant, α is the film coefficient h_i for unit water velocity (h_i = α). For a clean tube $R_i = 0$, thus the heat transfer coefficient h_o can be found directly from the intercept[4].

Results

The results shows variations of overall heat transfer coefficient as a function of water flow rate at atmospheric pressure. The heat flux and overall heat transfer coefficient decrease as the water flow rate decrease. Wilson plot shown in Figures 2 and 3 below provides the means of determining the individual film heat transfer coefficient for films and dropwise condensation at atmospheric pressure.

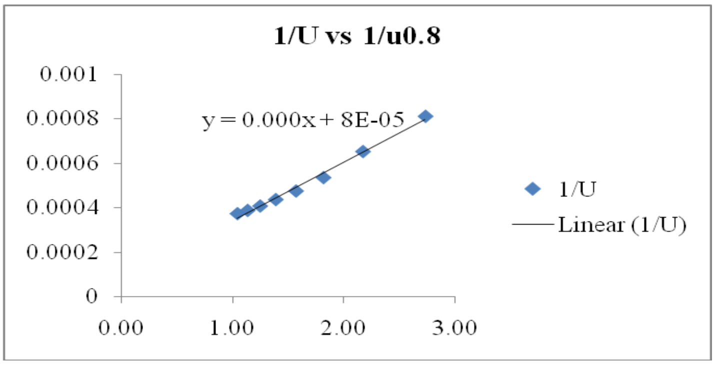

Figure 2.Plot of $\frac{1}{U}$ vs $\frac{1}{U^{0.8}}$(filmwise condensation)

Heat tranfer coefficient h_o was calculated from the intercept, i.e.,

$$\frac{1}{h_o} = 8 \times 10^{-5}, h_o = 12500 \text{W/m}^2\text{K}$$

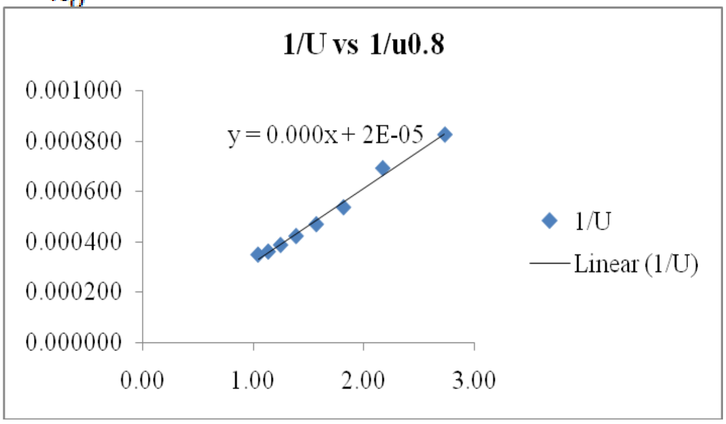

Figure 3. Plot of $\frac{1}{U}$ vs $\frac{1}{U^{0.8}}$ (dropwise condensation)

Heat transfer coefficient was calculated from the intercept, i.e.,

$$\frac{1}{h_o} = 2 \times 10^{-5}, \; h_o = 50000 \text{ W/m}^2\text{K}$$

Discussion

The value of heat transfer coefficient is 50000 W/m^{2}K in dropwise and 12500W/m^{2}K in filmwise condensation. The temperature driving force ΔT, was significantly lower in dropwise compared to filmwise condensation at the same value of heat flux; this may be due to the presence of numerous microscopic sized droplets on the hydrophobic surfaces in dropwise which do not exist in filmwise condensation [2].

In similar experiments, steady dropwise condensation of steam was observed on a plate coated with polyethenefluoroethylene (PTFE), the condensation heat transfer was increased by 30 to 47 times at the same surface subcooling degrees compared to filmwise condensation[5]. Hydrophobic coatings created through self-assembled monolayer of n-octadecyl mercaptan on copper alloy surfaces increased the condensation heat transfer rate by about eight times when compared with film condensation [2]. The overall heat transfer coefficient during dropwise condensation of ethyl alcohol, methyl alcohol, and acetone on a PTFE-coated condensing surface were approximately 30 percent for ethyl alcohol, 45 percent greater for methyl alcohol, and 65 percent for acetone than those during filmwise condensation on a bare iron tube [1].

Marto et al. and Holden et al. [6, 7] independently examined the effectiveness of several organic coatings to promote the dropwise condensation of steam. The results indicated that the steam dropwise condensation heat transfer coefficients for the surfaces coated with organic films are 3-8 times larger than those during filmwise condensation value for bare surface. Similarly, [8] employed thin film of polyvinylidene chloride to promote dropwise condensation of steam; the condensation heat transfer coefficient was more than 20 times than that for film condensation on bare surface.

Conclusions

The effect of coating the condensing surface with oleic acid on the condensation heat transfer characteristics was studied.Excellent dropwise condensation was observed on the pipe coated with oleic acid, it enables condensation of the steam in drops without wetting the condensing surface. On the other hand, continuous stream lines were flowing during film condensation. The heat transfer coefficient during dropwise condensation was found to be four times higher than those during filmwise condensation.

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