FLOODING DURING REFLUX CONDENSATION OF STEAM IN AN INCLINED ELLIPTICAL TUBE

P.D. Schoenfeld*   D.G. Kröger†

In this experimental investigation the pressure drop is measured between the headers located at the ends of an inclined air-cooled elliptical tube in which reflux condensation of steam occurs. The cross-section of the 7 m long tube has a height of 97 mm (major axis) and a width of 16 mm (minor axis). Steam temperatures are in the range of 45° C to 65° C. The pressure drop can be predicted accurately using the Zapke-Kröger pressure drop model applicable to reflux condensers. At a certain steam flow rate a sudden sharp increase in the pressure drop occurs. This phenomenon is known as flooding. The measured vapour velocities at flooding agree well with the values predicted by the Zapke-Kröger flooding correlation. The experimental results also show that flooding has a detrimental effect on the thermal effectiveness of the elliptical tube.

Nomenclature

A	Area (m²)
c_{pa}	Specific heat of air (J/kgK)
d_H	Hydraulic diameter (m)
e	Heat exchanger effectiveness
G	Gravitational acceleration (m/s²)
H	Height of duct (m)
i_{fg}	Latent heat of vaporization (J/kg)
K	Dimensionless constant, eqn (3)
m	Mass flow rate (kg/s)
n	Dimensionless constant, eqn (4)
Q	Heat transfer rate (W)
T	Temperature (°C)
v	Velocity (m/s)
μ	Dynamic viscosity (kg/ms)
ρ	Density (kg/m³)
σ	Surface tension (N/m)
θ	Inclination angle (degrees)

*Department of Mechanical Engineering, University of Stellenbosch, Private Bag X1, Matieland, 7602 South Africa

†Department of Mechanical Engineering, University of Stellenbosch

Subscripts

a	air
c	cross-section
d	diameter
fl	flooding
i	inlet
l	liquid
s	steam, superficial
t	tube
v	vapour

Dimensionless groups

$Fr_{Hsv} = \rho_v v_{sv}^2 / [(\rho_l - \rho_v) g H]$	Superficial densimetric vapour Froude number
$Fr_{Hsl} = \rho_l v_{sl}^2 / [(\rho_l - \rho_v) g d_H]$	Superficial densimetric liquid Froude number
$Re_{sv} = \rho_v v_{sv} d_H / \mu_v$	Superficial vapour Reynolds number
$Zk = \sqrt{(\rho_l d_H \sigma)}/\mu_l = Oh^{-1}$	Dimensionless liquid property parameter

Introduction

Forced draft air-cooled steam condensers are increasingly used in power generating plants, especially in arid regions. The condensers consist of bundles of finned tubes arranged in an A-frame configuration above the fans as shown in Figure 1(a).

The inclination angle of the finned tubes, which generally have a round, elliptical or flat-profile cross-sectional geometry, is approximately 60° to the horizontal. In the finned tubes the steam and condensate flow concurrently downward into the drainage header. To prevent subcooling of the condensate and the formation of dead zones due to the accumulation of non-condensable gases in the condenser, a secondary reflux condenser or dephlegmator is connected in series with the main condenser. The dephlegmator ensures that there is a net outflow of steam from the bottom of the main condenser. This steam condenses in a reflux mode in the dephlegmator, the steam flow being upwards countercurrent to the condensate flow. Non-condensable gases that may have leaked into the system are removed at the top of the dephlegmator by means of an ejector.

Since the dephleghmator operates in the reflux condensation mode, flooding of the dephlegmator can occur. At a so-called flooding vapour inlet velocity, the condensate does not drain freely into the bottom header of the dephlegmator, but starts to accumulate in the tubes. This results in a large pressure drop across the dephlegmator headers as well as a decrease in the thermal effectiveness of the dephlegmator.

Numerous studies have been conducted to investigate the pressure drop and flooding in reflux condensers. Banerjee et al.,[1] Girard & Chang[2] and Obinela et al.[3] studied reflux condensation of steam in a vertical water-cooled glass tube with the top and bottom header pressures held constant during an experimental run. Russell[4] made use of a long air-cooled finned tube inclined at 57° to the horizontal in which steam at atmospheric pressure was condensed. The various flow modes were observed through a sight-glass. Reuter & Kröger[5] conducted experiments in a vertical and inclined water-cooled glass tube in which low pressure steam was condensed in the reflux condensation mode. Bellstedt[6] studied reflux condensation of low pressure steam in an air-cooled finned tube inclined at 60° to the horizontal. Groenewald[7] conducted similar experiments in a flattened finned tube.

In this study the pressure drop and flooding during reflux condensation of low pressure steam is investigated in an air-cooled elliptical finned tube inclined at 60° to the horizontal. The experiments were conducted in a steam temperature range from 45°C to 65°C.

Experimental apparatus

The experimental apparatus is schematically depicted in Figure 1(b). Hot water (2), electrically heated, is pumped through a shell-and-tube heat exchanger (1) in which low pressure steam is generated. The steam is ducted to the steam inlet header (4) which has radial inlet and guide vanes that ensure that the steam is vortex free on entering the test tube. The test tube (5) is an elliptical finned tube, 7 m long and with an inside height (major axis) and width (minor axis) of 97 mm and 16 mm, respectively. The inlet of the tube is square-edged (90°). The cross-sectional area of the tube, $A_{ct} = 1333$ mm^2 and the hydraulic diameter, $d_H = 25.922$ mm. A top header (6) is connected to the upper end of the tube. A water-driven vacuum pump (7), connected to the system at the outlet header, is used to obtain subatmospheric pressures in the system prior to an experimental run and to remove non-condensable gases that may collect in the tube during a run. The entire finned tube is mounted in a wooden casing (8), which also forms part of a support frame. The frame is hinged at its lower end, thus making it possible to adjust the inclination angle of the tube. In this investigation the tube is at an angle of

60°. An air outlet manifold (9) is mounted on top of the wooden casing and is connected to a centrifugal fan (10) which draws cooling air across the finned tube.

During an experimental run the air inlet and outlet temperatures as well as the steam temperatures in the inlet and outlet headers are measured using copper constantan thermocouples. Calibrated propeller-type anemometers (11), situated in each lateral of the air outlet manifold, measure the air volume flow rate over the finned tube while a pressure transducer measures the differential pressure between the inlet and top headers of the tube. The steam condensation rate is determined using a measuring cylinder (3) that is attached to the steam generator.

Experimental results

The pressure drop and flooding in the elliptical finned tube were investigated using steam ranging in temperature from 45°C to 65°C. It was found that the header-to-header pressure drop can be predicted accurately using a two-phase pressure drop model applicable to reflux condensers as was proposed by Zapke & Kröger.[8,9] According to Zapke & Kröger[9] the pressure drop is both a function of the vapour Reynolds number and the densimetric vapour Froude number. At low vapour flow rates the pressure drop is Reynolds number related. However, at high vapour flow rates greater liquid-vapour interaction takes place, resulting in wave formation on the surface of the liquid. The vapour Froude number therefore becomes the governing dimensionless group and the duct height the characteristic dimension. The pressure drop in the elliptical tube as predicted by the Zapke-Kröger pressure drop model is compared to experimental header-to-header pressure drop data as a function of the vapour superficial velocity at the tube entrance as shown in Figure 2. Note that it is more meaningful to plot the pressure drop data in terms of the vapour velocity since the pressure drop is a function of both the vapour Reynolds number and Froude number.

As was mentioned above, at high vapour velocities the densimetric vapour Froude number becomes the governing dimensionless group. At a certain vapour velocity, namely the flooding velocity, a sharp increase in the header-to-header pressure drop occurs. The fact that flooding is governed by the vapour Froude number as opposed to the vapour Reynolds number is clear when considering Figures 3 and 4. They are plots of the pressure drop in the tube versus the vapour Reynolds number and densimetric vapour Froude number, respectively. In Figure 3, the flooding vapour Reynolds number varies between approximately 13 000 and 20 000 depending on the steam temperature. In terms of the Froude number, flooding occurs at approximately 0.47 irrespective of the
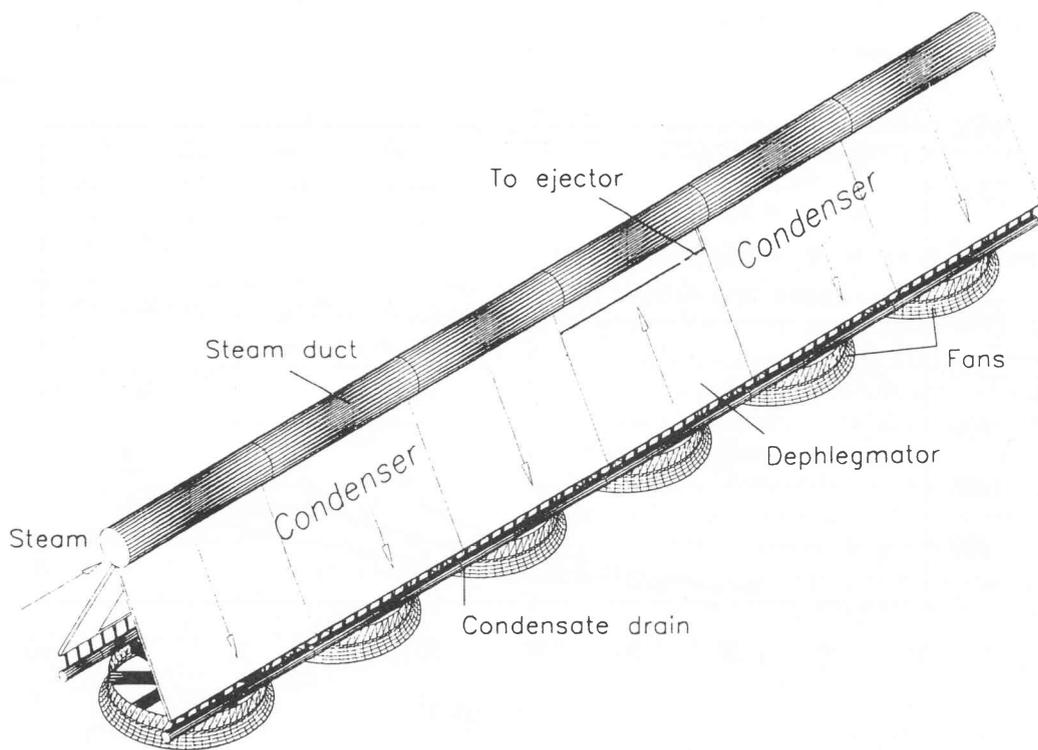
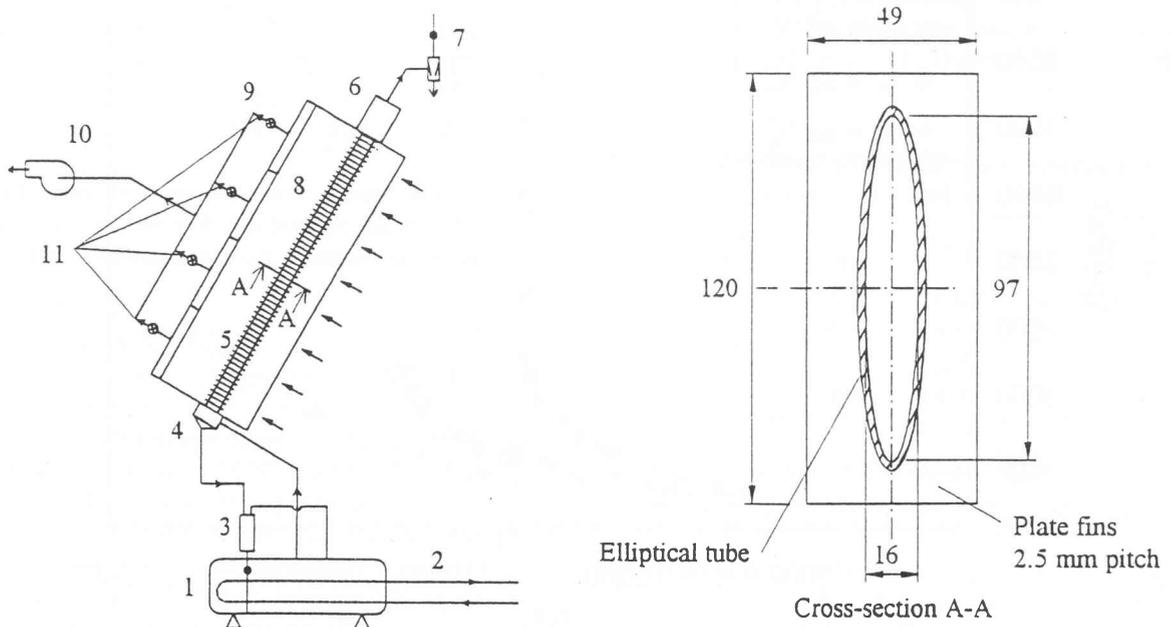Figure 1(a) Condenser with dephlegmator

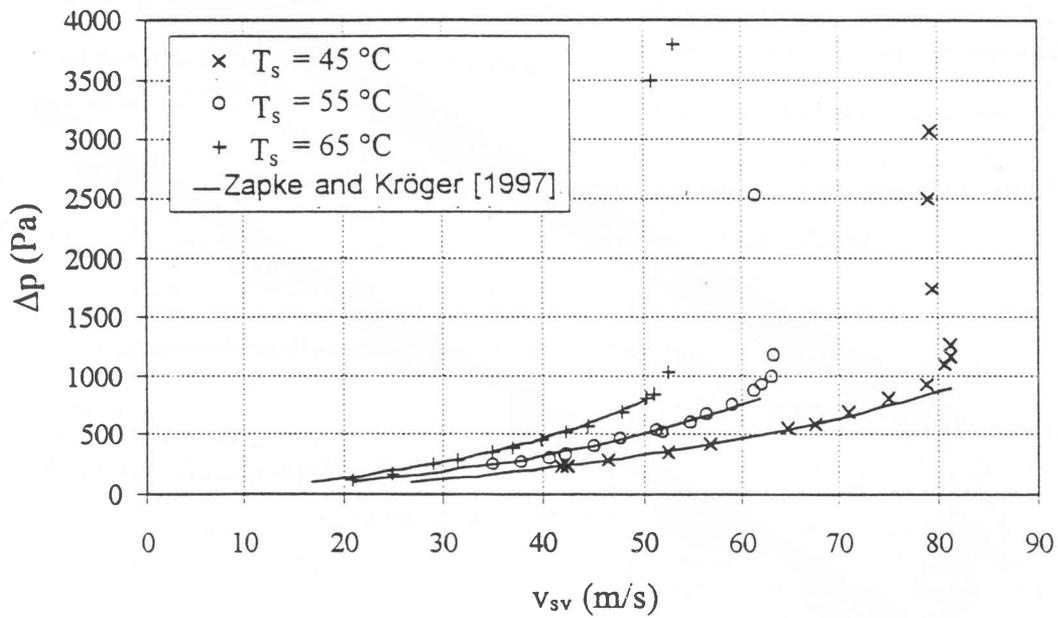Figure 1(b) Schematic representation of the experimental apparatus

Figure 2 Header-to-header pressure drop in an elliptical reflux condenser tube with a square-edged inlet
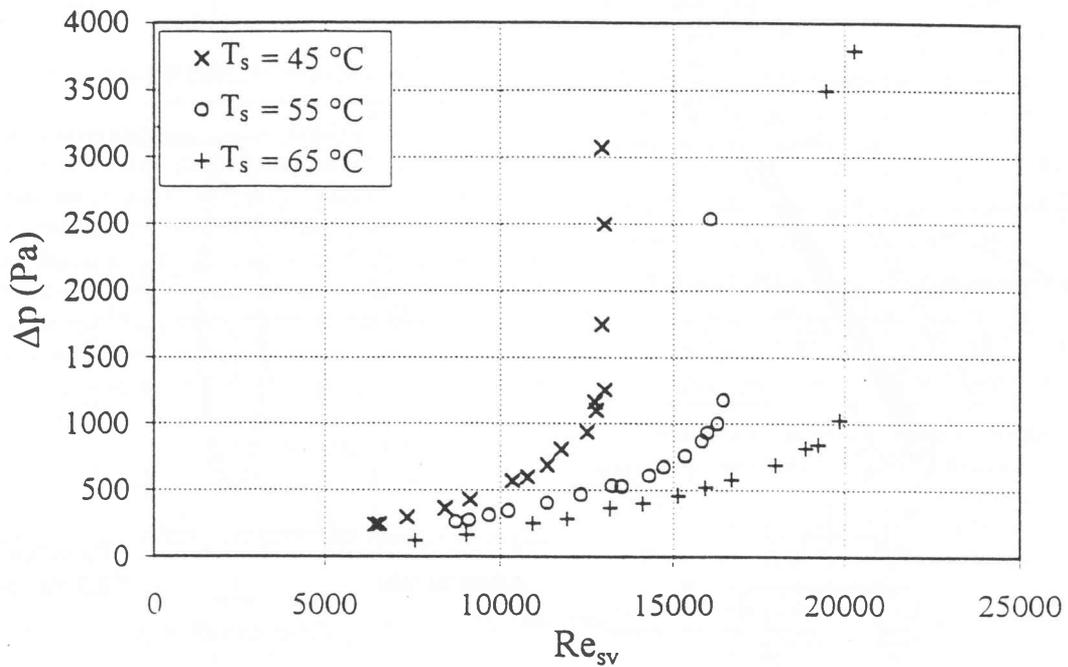

Figure 3 Total pressure drop in the elliptical reflux condenser tube versus the superficial vapour Reynolds number

steam temperature, as shown in Figure 4. The slight variation in the flooding vapour Froude numbers is due to the different condensate flow rates at the respective steam temperatures at flooding. Note that in Figure 4 the flooding vapour velocities, expressed in terms of the Froude numbers, have been indicated for the respective steam temperatures to clarify visually the definition of the flooding velocity.

Using various liquids and gases, Zapke[10] conducted adiabatic two-phase counterflow experiments in flattened tubes of different heights at inclination angles between 0° and 90°. The tubes had square-edged inlets (90°). Flooding was defined as that condition when the gas flow starts to carry the liquid up beyond the liquid feed point. At that condition a significant rise in pressure drop was observed. Zapke correlated the flooding data in terms of the superficial vapour Froude number expressed as a function of the liquid Froude number and a dimensionless number originally proposed by Zapke & Kröger,[8] i.e.

$$Zk = \sqrt{(\rho_l d_H \sigma)}/\mu_l = Oh^{-1} \qquad (1)$$

which accounts for the liquid properties. Oh is the Ohnesorge number. The correlation takes into account the effect of tube geometry (height and hydraulic diameter) and inclination angle, and is expressed as

$$Fr_{Hsv} = K_{fl} \exp\left(-n_{fl} \times Fr_{dsl}^{0.6} \times Oh_{d_H}^{0.2}\right) \qquad (2)$$

where

$$K_{fl} = 7.9143 \times 10^{-2} + 4.9705 \times 10^{-3} \times \theta$$
$$+ 1.5183 \times 10^{-4} \times \theta^2 - 1.9852 \times 10^{-6} \times \theta^3 \qquad (3)$$

and

$$n_{fl} = 18.149 - 1.9471 \times \theta + 6.7058$$
$$\times 10^{-2} \times \theta^2 - 5.3227 \times 10^{-4} \times \theta^3 \qquad (4)$$

with θ the inclination angle in degrees. In a reflux condenser tube the flooding fluid velocities and properties are such that the expression in brackets on the right-hand side of eqn (2) is very small. Therefore, by making use of the Taylor series expansion for an exponential function and neglecting second and higher order terms, eqn (2) may be written approximately as

$$Fr_{Hsv} \approx K_{fl}\left(1 - n_{fl} \times Fr_{dsl}^{0.6} \times Oh_{d_H}^{0.2}\right) \approx K_{fl} \qquad (5)$$

At an angle of inclination of $\theta = 60°$ this equation is further simplified to

$$Fr_{Hsv} \approx 0.49516\left(1 - 27.7615 \times Fr_{dsl}^{0.6} \times Oh_{d_H}^{0.2}\right) \qquad (6)$$
$$\approx 0.49516$$

It should be noted that Fr_{Hsv} is based on the height of the duct while Fr_{dsl} is based on the hydraulic diameter of the duct.

As mentioned previously, Reuter & Kröger[5] conducted reflux condensation experiments in a glass tube with an inside diameter of 30 mm. Their flooding data and the experimental flooding data obtained in this investigation are plotted in the form of the superficial densimetric vapour Froude number versus a product of the liquid densimetric Froude number and the Ohnesorge number as shown in Figure 5.

Numerous researchers [Banerjee et al.,[1] Girard & Chang,[2] Obinelo et al.,[3] Reuter & Kröger[5]] have suggested that flooding determines maximum heat transfer in a tube in which all the steam condenses in the reflux mode.

Since the superficial vapour velocity at the tube entrance is representative of the heat transferred, it is useful to express the flooding data in terms of the flooding velocity. Upon rearranging eqn (6), the predicted flooding velocity at the tube entrance can be expressed as

$$v_{sv} \approx 0.70367\left[(\rho_l - \rho_v)gH\left(1 - 27.7615 \times Fr_{dsl}^{0.6} \times Oh_d^0\right.\right.$$
$$\approx 0.70367\left[(\rho_l - \rho_v)gH\right]^{0.5} \qquad (7)$$

where H is the duct height for an elliptical tube, or the diameter for a round tube. The right-hand side of eqn (7) is dependent on the fluid properties which are temperature dependent. It is therefore possible to express the flooding vapour velocities in terms of the steam temperatures. This has been done graphically in Figure 6 where eqn (7) is compared to experimentally determined flooding vapour velocities for the elliptical tube studied in this investigation as well as the 30 mm tube used by Reuter & Kröger.[5]

Under ideal conditions, i.e. flooding does not occur irrespective of the heat transfer, it is possible to calculate the ideal heat transfer rate of an air-cooled reflux condenser tube using the air mass flow rate and air inlet temperature flowing over the tube as follows:

$$Q_{ideal} = e\, m_a c_{pa}\left(T_s - T_{ai}\right) \qquad (8)$$

The effectiveness e in eqn (8) is a function of the overall heat transfer coefficient U, which in turn is a function of the condensation heat transfer coefficient. In the case of 'ideal' heat transfer the condensation heat transfer coefficient for film condensation is used to calculate U. Once flooding occurs the film condensation heat transfer coefficient is not valid anymore and conditions are no longer 'ideal'. This is the reason for the deviation depicted in Figure 7.

The ideal superficial vapour velocity at the tube entrance corresponding to the ideal heat transfer rate is
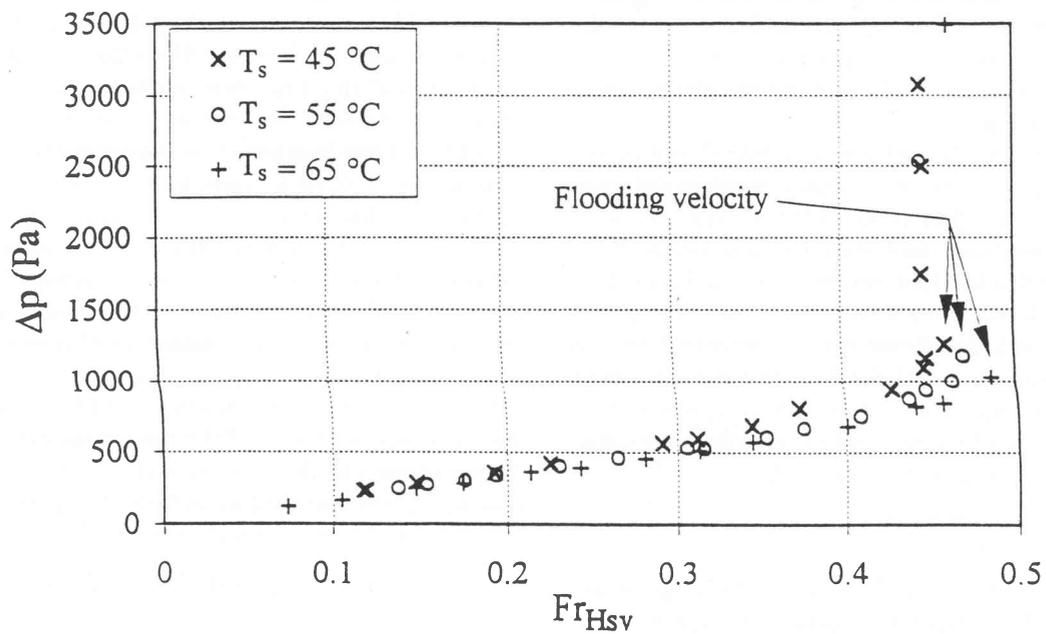
Figure 4 Total pressure drop in the elliptical reflux condenser tube versus the superficial densimetric vapour Froude number
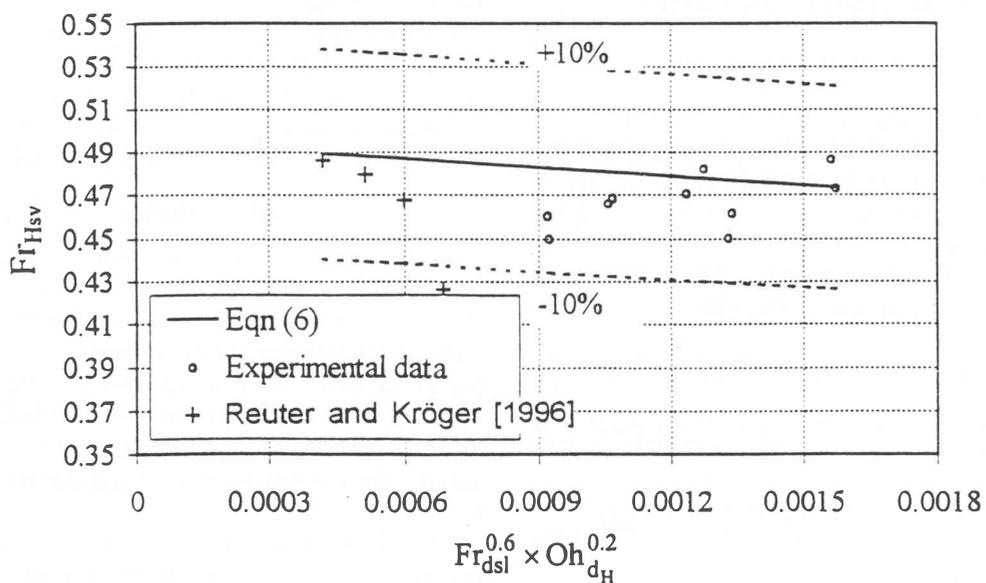

Figure 5 Flooding superficial vapour Froude number at the tube entrance
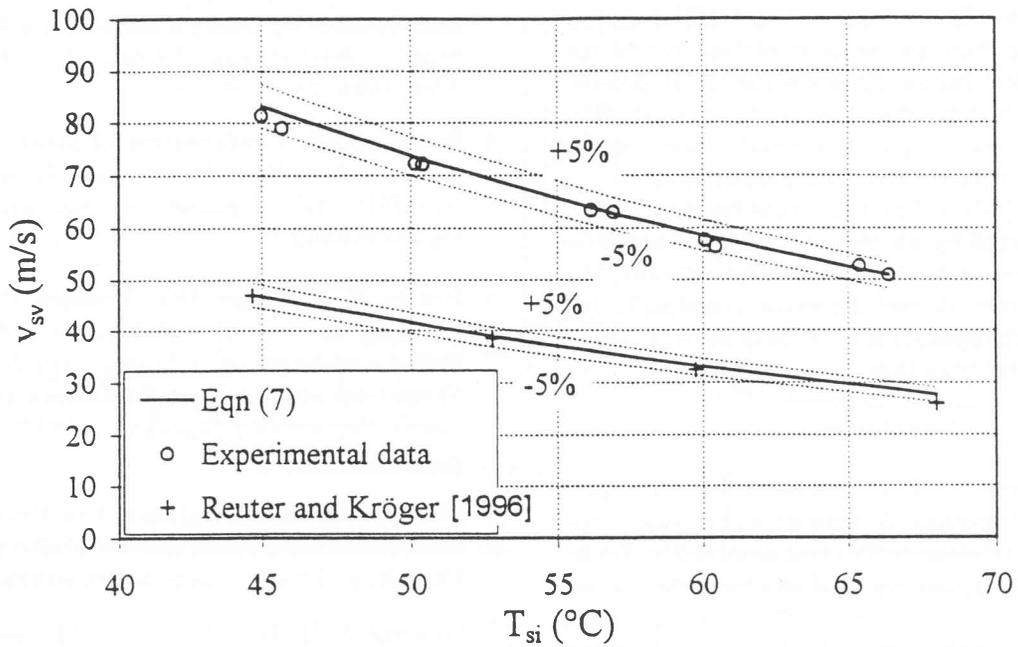
Figure 6 Flooding vapour velocity at the tube entrance as a function of the steam inlet temperature
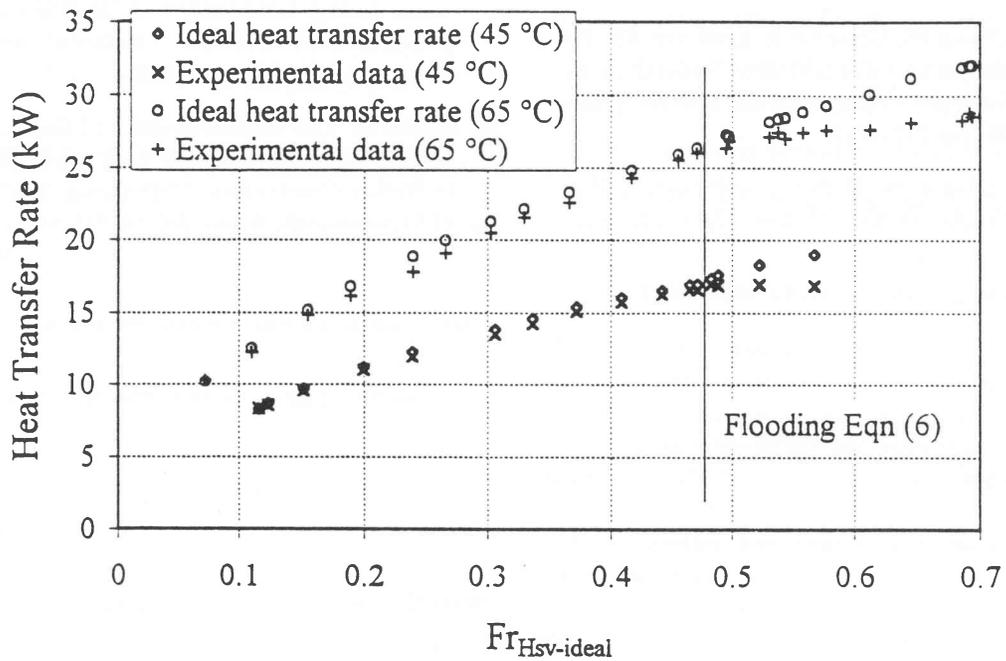

Figure 7 Ideal and experimental heat transfer rates versus vapour Froude number corresponding to ideal heat transfer rate

then

$$v_{sv-\text{ideal}} = Q_{\text{ideal}}/\left(i_{fg}\rho_v A_{ct}\right) \qquad (9)$$

from which the vapour Froude number can be calculated. In Figure 7 the ideal heat transfer rate calculated assuming that flooding does not occur is plotted versus the corresponding ideal vapour Froude number. To demonstrate the effect that flooding has on the thermal effectiveness of a reflux condenser, the measured heat transfer rate is also plotted versus the ideal Froude number.

Figure 7 clearly shows the effect that flooding has on the heat transferred by an air-cooled reflux condenser tube. When flooding occurs in the elliptical tube, the thermal effectiveness thereof decreases, resulting in the actual heat transfer rate being lower than the heat transfer rate under ideal conditions.

Conclusion

The pressure drop in a reflux condenser tube can be predicted using the two-phase flow pressure drop model applicable to reflux condensers that was proposed by Zapke & Kröger.[9] As is the case for adiabatic flow, the vapour Froude number is the governing dimensionless group at flooding in reflux condensers. The flooding correlation proposed by Zapke[10] for flooding during adiabatic countercurrent flow can be simplified and applied with confidence to determine the flooding velocity at the inlet to reflux condenser tubes or ducts wherein steam between 45°C and 65°C is condensed. It has also been shown that a decrease in the thermal effectiveness of a dephlegmator occurs at flooding.

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