Title

CONDENSATION FILM COEFFICIENTS FOR MIXTURES OF ISOBUTANE AND ISOPENTANE

Authors

Tleimat, B.W.
Rie, H.
Laird, A.S.K.
et al.

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DISCLAIMER

CONDENSATION FILM COEFFICIENTS FOR MIXTURES OF ISOBUTANE AND ISOPENTANE

B. W. Tleimat, Principal Development Engineer
H. Rie, Engineer*
A. D. K. Laird, Professor of Mechanical Engineering and Director
S. Zhao, Research Associate

Sea Water Conversion Laboratory
University of California
47th & Hoffman Blvd.
Richmond, California 94804

Abstract

Research designed to obtain baseline data on heat transfer for working fluids in geothermal binary cycle systems is described. The working fluid loop in the experimental apparatus simulates the binary cycle with steam as the heating fluid and a throttling valve instead of the turbine. In this paper, data on film coefficient for the condensation of 90/10 and 80/20 mixtures of isobutane-isopentane on a horizontal tube at various temperatures and condensation rates are presented. Data indicate that mixtures of isobutane-isopentane have lower condensation film coefficients than that of the pure isobutane under equivalent conditions of temperatures and condensation rates. Depending on the mass condensation rate, the film coefficient for the 80/20 mixture can be as low as 30 percent of the film coefficient for pure isobutane at the same mass condensation rate.

Introduction

In geothermal power plants using the binary cycle, the cost of heat-transfer equipment accounts for approximately half the capital cost[1]. Inexact estimate of the heat-transfer coefficients can have serious consequences. If the estimated coefficients are too high, the plant may fail to meet its performance guarantee; if much too low, the plant will be overdesigned and wasteful.

Analysis[2] of geothermal binary cycle systems using medium temperature brines indicated that the use of mixtures of light hydrocarbons as the working fluid can result in higher efficiencies than can be obtained through the use of pure components alone. In studies [3,4], sponsored by the Electric Power Research Institute, of geothermal binary cycle demonstration plants two mixtures of light hydrocarbons were identified as the most suitable to correspond with the depletion of geothermal reservoirs in the Imperial Valley, California. In the first[3], the plant would start with pure isobutane and then add propane gradually so that the mixture would be 65 percent isobutane and 35 percent propane at the end. In the second study[4], a 90/10 percent isobutane-isopentane was found to be optimum for the life of the plant.

During the condensation of binary mixtures, the more volatile component acts as a noncondensable gas and decreases the diffusion rate of the less volatile component. Although condensation of binary mixtures has been analyzed[5], reliable thermodynamic and transport properties are needed to evaluate film coefficient. Comparison of published data[6] on condensation of binary mixtures showed as much as 80 percent variation. The lack of reliable data[7] on transport properties, as well as the need for realistic condensation coefficients for the design of condensers in binary cycle plants, made it expedient to obtain data for the desired mixture at the anticipated operating conditions of the plant.

The binary fluid experiment was designed to provide laboratory quality experimental data on heat-transfer film coefficients for heating and condensation of various candidate working fluids and to study the effects of contaminants on performance. This experiment is part of an overall program supported by the Division of Geothermal Energy of the U.S. Department of Energy to obtain data for the design of heat-transfer equipment for geothermal plants using the binary cycle systems. The objective of this experiment was to provide data under controlled conditions with clean surfaces to determine heat-transfer film coefficients of various candidate working fluids for heating, boiling and condensation. This paper presents data on the condensation of mixtures of isobutane-isopentane on a horizontal tube at temperatures ranging from 50 to 105C, and condensation rates ranging from 45 to 450 Kg per hour per square meter of heat-transfer surface (10 to 100 lbs/hr ft^2).

Experimental Apparatus and Procedure

Figure 1 is a schematic flow diagram of the apparatus. The experimental equipment consists of

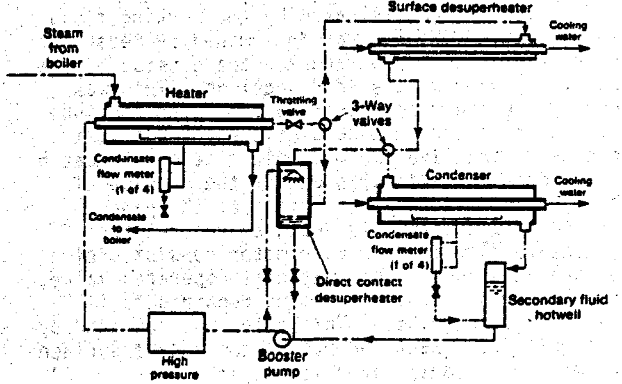

Fig. 1 Binary fluid experiment, schematic flow diagram.

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*Envirotech-Sephton Development Center, Emeryville, Calif.
Member AIAA

a stainless steel loop simulating a binary system with steam instead of geothermal brine as the heating fluid and a throttling valve instead of the turbine. The pressurized working fluid is heated inside a tube by steam condensing on the outside of the tube. The fluid then expands through a throttling valve and is introduced into a direct contact desuperheater. After desuperheating the vapor enters the condenser and condenses on the outside of a single instrumented tube identical to that in the heater but having cooling water flowing inside. The condensed fluid is collected in the hotwell and enters the booster pump where it is slightly pressurized before entering the high pressure variable capacity diaphragm-type pump from which it flows through a turbine flow meter and preheater (not shown) and then enters the heater tube to close the cycle. When the expanded fluid is superheated, a portion of the liquid is diverted to the direct contact desuperheater and the excess is returned to the suction side of the booster pump.

The condenser tube was made from a 31.8 mm (1.25 in.) O.D. and 19.1 mm (0.75 in.) I.D.-type 316 stainless steel tube about 2.7 m (106 in.) long, and honed to an inside diameter of 19.2 mm (0.756 in.). In order to obtain uniform wall thickness, it was machined and ground to an outside diameter of 30.2 mm (1.189 in.). The concentricity was then checked by ultrasonic measurement of the tube wall thickness at 101.6 mm (4.0 in.) intervals along the axis. At each location, the wall thickness was measured at four points 90° apart. These measurements gave the precise locations of thermocouples imbedded in the wall of the tube. Fifteen thermocouples were imbedded in the wall of the tube at five stations, 609.6 mm (24 in.) apart, with three thermocouples located at each station. The inside and outside surface temperatures of the tube at each of the five stations were calculated from radial heat conduction through the tube wall from the measured temperatures at the known locations of the thermocouples.

The temperature profile of the condensing vapor outside of the condenser tube was determined by means of a calibrated RTD and seventeen calibrated type K thermocouples located in the vapor space. The RTD was located at the opposite end from the vapor inlet, while the seventeen thermocouples were located at six-inch intervals spanning the five stations along the length of the tube.

The rate of heat released by the working fluid vapor in the condenser was determined by measuring the rate of condensing vapor on the outside of the tube along each of the four sections. This was done by placing a four-section pan under the tube with the five ends of the sections located just underneath the five thermocouple stations to catch the condensate as it dripped off the outside of the tube. The separate sections of the pan drained into a specially designed vapor-traced condensate flow meter. Each meter consisted of a calibrated volume, a pneumatically operated valve, and a timer to measure the time required to fill the calibrated volume. This timer was operated by photocells to detect the rising condensate surface between two predetermined levels in the meter. A sampling valve at each of the four meters was provided so that composition of the condensate from each of the four sections could be determined. A cross section of the external shell, the instrumented tube with thermocouples at 45° from vertical plane, the condensate pan and the hood placed above the tube to prevent condensate forming on the inside surface of the shell from dripping into the pan are shown in Fig. 2 for the condenser.

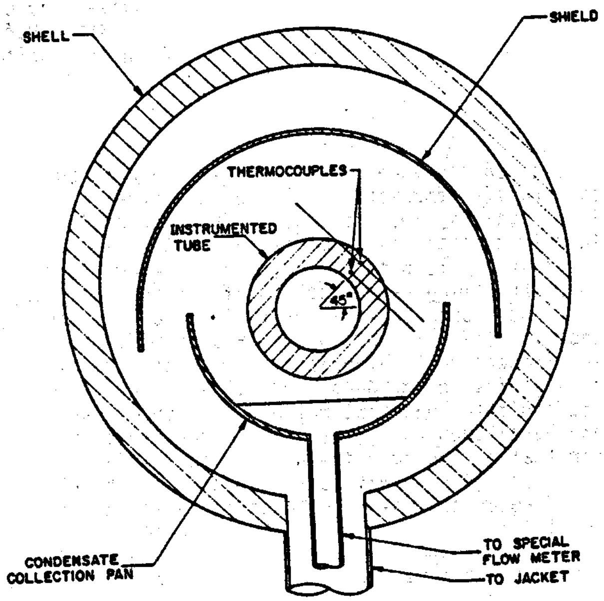

Fig. 2 Condenser cross section showing tube, condensate tray, drip shield and outer shell.

Results and Discussion

The results reported in this paper were obtained for the condensation of two mixtures: 90/10 and 80/20 mole percent isobutane/isopentane. The data were obtained at saturation temperatures ranging from 50 to 105C (122 to 220°F) and for condensation fluxes ranging from 45 to 450 Kg/hr m^2 (10 to 100 lbs/hr ft^2).

Figures 3 and 4 show the condensation film coefficient, h, for the 90/10 and 80/20 mixtures, respectively, as a function of the dimensionless number $2\Gamma/\mu$. Γ is the condensate mass rate per unit length of tube and μ is the viscosity of pure liquid isobutane at the film temperature $t_f = t_v - 0.75\,(t_v - t_w)$, where t_v is the vapor temperature and t_w is the outside tube wall temperature. The average film coefficient, h, for each section was calculated from the equation

$$h = \frac{Q}{A\,\Delta T_m}$$

where Q is the heat rate for each section as determined from measurement of the mixture condensate rate and its latent heat, A, is the outside surface area of the tube per section, and ΔT_m is the logarithmic mean temperature difference between the vapor temperatures and outside wall temperatures at both ends of each section.

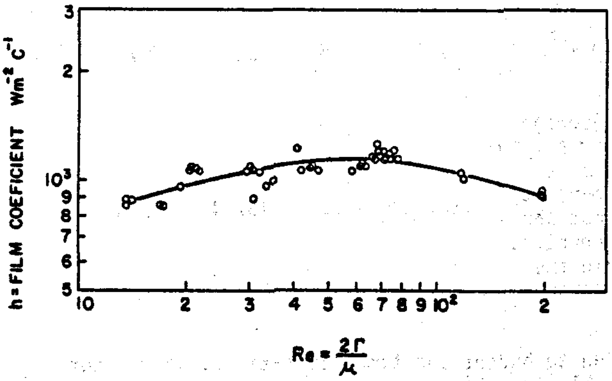

Fig. 3 Film coefficient for condensation of 90/10 mol-percent mixture of isobutane/isopentane on a horizontal tube as a function of Reynolds Number.

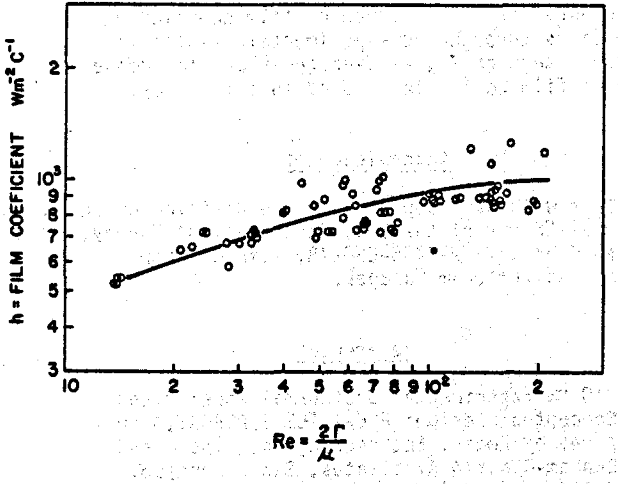

Fig. 4 Film coefficient for condensation of 80/20 mol-percent mixture of isobutane/isopentane on a horizontal tube as a function of Reynolds Number.

Figures 5 and 6 show dimensionless plots of the data shown on Figs. 4 and 5, respectively, as a function of $4\Gamma/\mu$. Due to lack of reliable data on transport properties of mixtures and for consistency with previous publications from this experiment[8,9], values of transport properties of isobutane as given by Hanley[10] were used as the basis for the plots of Figs. 3, 4, 5 and 6. For comparison, the straight lines in Figs. 5 and 6 show the Nusselt prediction for a pure component while the other lines in Figs. 3, 4, 5 and 6 were drawn through the average values of the ordinates.

Figure 7 shows the ratio h/h_N as a function of the temperature difference between the vapor in the condenser shell and the outside wall of the tube. Here h is the condensation film coefficient as determined from the data for the two mixtures and h_N is the film coefficient for pure isobutane as calculated from the Nusselt correlation using the transport properties given by Hanley[10].

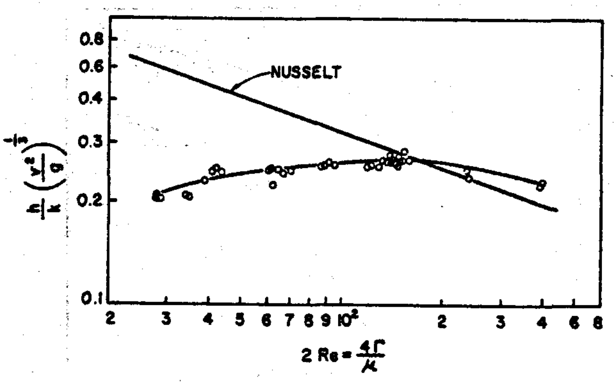

Fig. 5 Dimensionless plot of data on condensation of 90/10 mol-percent mixture of isobutane/isopentane on a horizontal tube. Solid line shows the Nusselt correlation for pure substances.

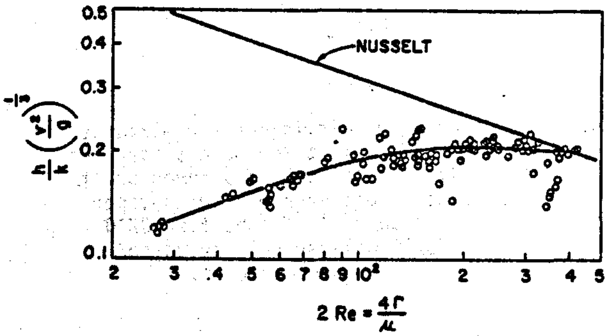

Fig. 6 Dimensionless plot of data on condensation of 80/20 mol-percent mixture of isobutane/isopentane on a horizontal tube. Solid line shows the Nusselt correlation for pure substances.

Inspection of Figs. 3, 4, 5, 6 and 7 shows scatter in the data at medium and high values of Reynolds number. This scatter could be due to at least two factors: carryover of liquid droplets from the direct contact desuperheater into the condenser and variation of composition of condensate and vapor along the length of the condenser tube.

It was observed during runs with medium and high condensation rates that the time required to fill the calibrated volume of the condensate flow meter under the first and second sections of the tube became erratic and unrepeatable. The higher the condensate rate, the more erratic the behavior. Visual observation of the vapor space through the sight glasses above and below the calibrated volume revealed falling liquid droplets. Because of the construction of the meter, this cannot occur except in the case of high carryover of liquid droplets with the vapor stream. When the droplets were fine and did not

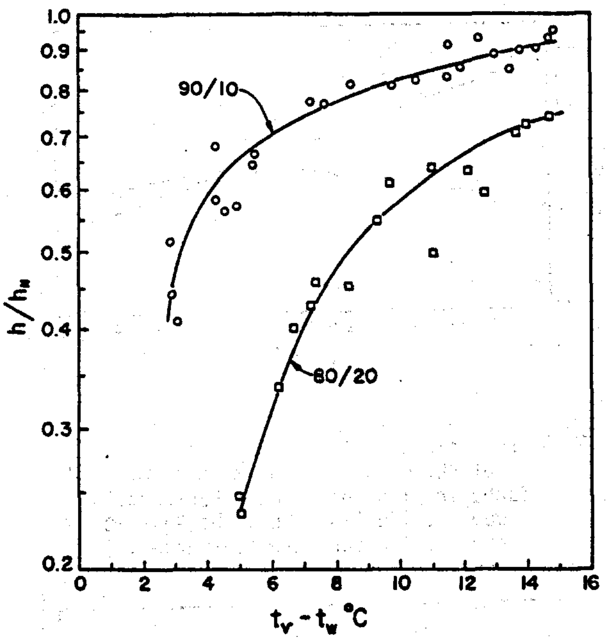

Fig. 7 Ratio of film coefficient for mixtures to film coefficient for pure substances (Nusselt correlation) as a function of temperature difference between vapor and outside wall of tube for 90/10 and 80/20 mol-percent isobutane/isopentane mixtures.

affect the repeatability of timing measurements, they caused an apparent increase of the film coefficient of the first two sections.

The variation of composition along the length of the condenser tube affected the condensation film coefficient because the vapor entering the condenser is at the dew-point of the mixture and the condensate that forms first on the tube is richer in the higher boiling point isopentane than the original composition. As the condensation continues along the tube, the compositions of both the vapor and condensate become leaner in isopentane. Sparrow and Marschall[5] predicted that, for binary mixtures of methanol water vapor, the film coefficient for a constant temperature difference between the vapor and the wall approaches that of the pure substance as the composition of the less volatile component increases. Because the condensate from each of the four pans was metered and sampled separately, it was possible to determine the average condensation coefficient and composition for each of the four two-foot sections of the horizontal condenser tube. As an example of this effect, the results from a typical run on the 80/20 mixture were:

SECTION	A	B	C	D
h $Wm^{-2}C^{-1}$	795	846	869	897
Average composition mole percent isobutane/isopentane in the condensate	56/44	70/30	76/24	88/12

Due to budget and time limitations, it was not feasible to take samples during all runs to determine compositions to correlate all the film coefficients with composition.

Based on the results shown, one can conclude the condensation film coefficient is significantly less than predicted by Nusselt's equation, particularly at lower values of Reynolds number, and that composition and temperature difference between the vapor and the outside wall of the tube have very strong influence on film coefficient. The lines through the experimental results in Figs. 3 through 7 give average values for condensation film coefficient found in this study.

Acknowledgment

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