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Shell-side boiling of water at sub-atmospheric pressures

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ABSTRACT

Experimental data are reported for water boiling at pressures of 850 and 50 mbar absolute on the shell-side of a model industrial boiler slice. The boiler test section was 1 m high, 0.75 m wide and contained 36 electrically heated tubes. The tubes were 28.5 mm in diameter and 98 mm long. The design of the boiler ensured that the tubes were submerged in a liquid pool. The height of the liquid pool could be varied. The pool height was set to approximately 0.8 m for the tests carried out at a pressure of 850 mbar, submerging the top of the tube bundle by about 200 mm. Two pool heights were used in the tests carried out at a pressure of 50 mbar, one at approximately 0.8 m and another at approximately 2 m. The later submerged the top of the tube bundle by about 1.6 m. The heat flux was varied within the range 10–70 kW/m^2. A near-symmetrical half of the tube bundle contained wall thermocouples. An additional 29 thermocouples were located throughout the liquid pool.

The liquid temperature in the pool was found to be reasonably uniform and controlled by the pressure at the free surface. This led to a small amount of subcooling at a pressure of 850 mbar, up to 3 K, and a significant amount of subcooling at a pressure of 50 mbar, up to 16 K for the smaller pool height and up to 31 K for the larger pool height. The reasonably uniform pool temperature suggests that the liquid re-circulates within it.

Boiling was found to occur at all heat fluxes at a pressure of 850 mbar, with the measured heat-transfer coefficients shown to be in broad agreement with nucleate boiling correlations available in the open literature. However, they were also consistent with a flow boiling process involving natural convection and nucleation, where the convection was driven by variations in liquid temperature on the walls of the tubes. This natural convection relies on an interaction between the tubes that produces mass fluxes in the range 46–87 kg/m^2 s, based on the approach area to the tube bundle. Boiling occurred only at the higher heat fluxes during the low level tests at a pressure of 50 mbar, with interactive natural convection being the dominant heat-transfer mechanism. The mass fluxes produced were in the range 28–70 kg/m^2 s. Boiling also occurred only at the higher heat fluxes during the high level tests at a pressure of 50 mbar. However, the convective heat transfer was more compatible with little interaction between the tubes, although some evidence suggests that the evaporator oscillates between interactive and isolated tube behaviour.

1. Introduction

Some evaporators, like those used to process nuclear waste, boil fluids that are highly corrosive. The corrosion rate of the materials used to construct these evaporators depends on their temperature. Thus, the life of the evaporator can be extended if the wall temperatures of the evaporator are kept low. One way of achieving this is to boil the fluid at a low pressure, and hence a low saturation temperature. This study was initiated to investigate the changes that occur in evaporator operation as the pressure is reduced. The investigation was carried out on a one-quarter scale, thin slice model of a bespoke industrial evaporator that is used in the processing of nuclear waste. The model evaporator could operate at any pressure from close to total vacuum to atmospheric and had a glass front to allow visual information to be obtained. The pressures investigated were 850 mbar, the HP series, and 50 mbar absolute, the LP series. The latter tests were carried out at two pool heights, one at approximately 0.8 m, the low level tests, and one at approximately 2 m, the high level tests.

The geometry of this thin slice model is similar to those used in the study of kettle reboilers. A review of these studies is given by

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McNeil et al. [1]. Most of these studies were carried out using pentane and refrigerant R113. This study used water.

The kettle reboiler is one of the most commonly used shell and tube heat exchangers in the process industry and consists of a tube bundle placed in a shell. The liquid level above the tube bundle is set by a weir. The heating fluid flows inside the tubes while the heated fluid boils on the outside surfaces of the tubes. The difference in densities between the two-phase mixture flowing shell side within the tube bundle and the liquid flowing between the tube bundle and the shell is known to cause natural circulation. The circulation flow rate is needed in the estimation of the local heat-transfer coefficient.

The simplest analytical approach available is the one-dimensional model, see for example Brisbane et al. [2] or Jensen [3]. This model assumes that liquid enters each column of the tube bundle from the bottom and evaporates as it moves vertically upwards. The two-phase pressure drop in a column is assumed to balance with its static head of liquid. This is based on reasonably static liquid being present between the tube bundle and the shell wall and could therefore be relevant to the model evaporator used in this study. The two-phase pressure drop has gravity, acceleration and friction components. A void fraction and a two-phase friction multiplier correlation are therefore required to complete the model. For conditions typical of kettle reboilers, Bamardouf and McNeil [4] have shown that the void fraction correlation of Feenstra et al. [5] and the two-phase multiplier correlations of Ishihara et al. [6] give the best agreement with the available experimental data, which was mostly obtained from one-dimensional flow experiments. The two-phase multiplier approach requires the liquid only pressure drop to be found. ESDU [7] was used by Bamardouf and McNeil [4]. When applied to thin kettle slices, the one-dimensional model has been shown to be consistent with its inherent assumptions at heat fluxes lower than 20 kW/m^2 by Burnside et al. [8].

Boiling at low (vacuum level) pressures has not had very much attention in the literature. Some pool boiling data has been reported. A reasonable summary is given by Feldmann and Luke [9]. The reduced pressure is the ratio of the pressure to the critical pressure and has a value of 0.00023 in this study. Only two data sets are reported in the literature to go that low, one by Minchenko [10] and another by Gorodov et al. [11]. The Minchenko [10] heat-transfer coefficient data is shown to be more than twice the magnitude of that reported by Gorodov et al. [11], with the later reasonably predicted by the Gorenflo [12] correlation and the former by the Cooper [13] correlation, with the correlation's coefficient increased in line with the recommendation for a copper horizontal cylinder.

2. Description of the test facility

The test facility is shown in Fig. 1. To fill the rig with deionised water, both drain valves and the vent condenser valve were closed and the vacuum pump control valve was opened, Fig. 1. The vacuum pump was switched on until the test section pressure was reduced to 500 mbar. The drain valve to the test section was opened, allowing water to flow from the storage tank to the evaporator. The drain valve was closed when the desired water level was achieved in the evaporator. The drain valve from the hot well was opened, allowing water to flow from the storage tank to the hot well. The drain valve was closed when the water reached the desired height in the hot-well sight glass. The circulating pump, water control valves and the evaporator entry shut-off valve were opened, allowing water to flow from the hot well to the vessel, purging any air from the pipe work. The shut-off valve was closed when a steady flow of water was evident in the evaporator.

To operate the rig, the vacuum pump was switched on and adjusted until the required test section pressure was achieved. Heat was supplied to the evaporator by Joule heating of rod heaters contained within the tubes. Initially, the tube heaters were

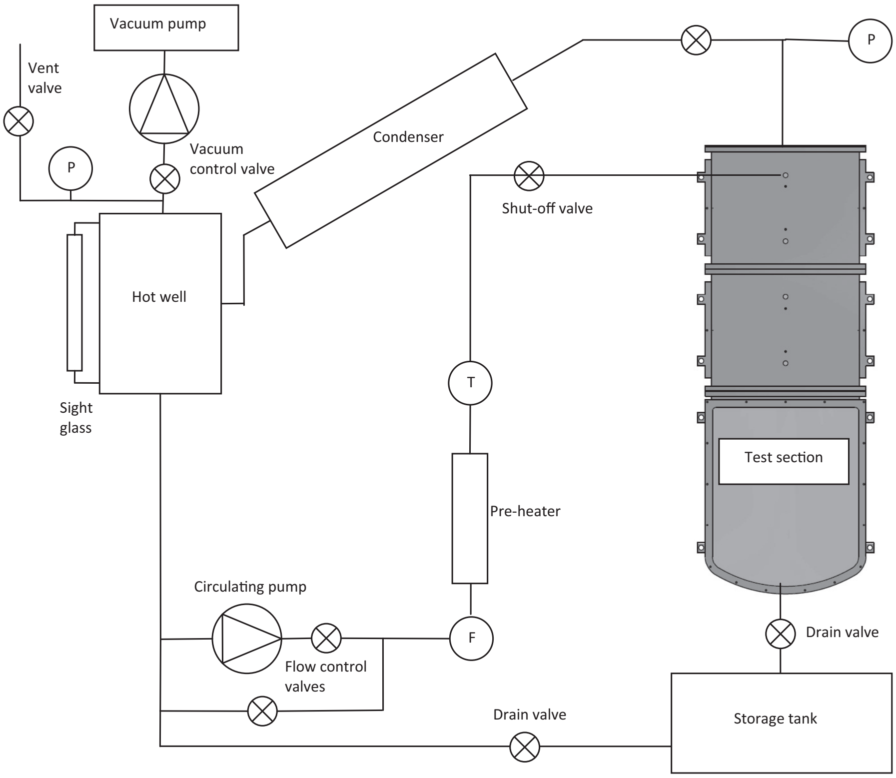

Fig. 1. Plant layout.