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A one-fluid, two-dimensional flow simulation model for a kettle reboiler

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ABSTRACT

A one-fluid, or algebraic slip, model has been developed to simulate two-dimensional, two-phase flow in a kettle reboiler. The model uses boundary conditions that allow for a change in flow pattern from bubbly to intermittent flow at a critical superficial gas velocity, as has been observed experimentally. The model is based on established correlations for void fraction and for the force on the fluid by the tubes. It is validated against pressure drop measurements taken over a range of heat fluxes from a kettle reboiler boiling R113 and n-pentane at atmospheric pressure.

The model predicts that the flow pattern transition causes a reduction in vertical mass flux, and that the reduction is larger when the transition occurs at a lower level. Before transition, the frequently-used, one-dimensional model and the one-fluid model are shown to predict similar heat-transfer rates because similar magnitudes of mass flux are predicted. After transition, the one-dimensional model significantly over-predicts the mass fluxes. The average heat-transfer coefficient predicted by the one-fluid model is consequently about 10% lower. The one-fluid model shows that tube dryout can be expected at much lower heat fluxes than previously thought and that the fluid kinetic energy available to induce tube vibrations is significantly smaller.

1. Introduction

Shell and tube heat exchangers are widely used in the process industry. One of the most commonly used designs is the kettle reboiler, which consists of a horizontal tube bundle placed in a shell. The heating fluid flows inside the tubes while the heated fluid boils outside the tubes, Fig. 1.

The design problem is essentially a three-dimensional one. Fluid is moved axially from the inlet end of the shell to the weir, as well as vertically and horizontally in cross sections perpendicular to the shell axis. The latter motion is the predominant one, and, once determined, can be incorporated into a fully three-dimensional design solution. The motion is due to natural circulation resulting from the difference in densities between the two-phase mixture flowing in the tube bundle and the liquid flowing between the tube bundle and the shell wall. To determine the circulation flow rate, different modelling approaches have been proposed.

The simplest approach is the one-dimensional model, [1–4], where saturated liquid is assumed to enter the bundle from the bottom and to evaporate while it moves vertically upwards. The two-phase pressure drop in the tube bundle is assumed equal to the static head of the liquid between the tube bundle and the shell wall. Since the two-phase pressure drop has gravitational, acceleration and frictional components, the void fraction and a two-phase friction multiplier are required to complete the model. Several investigators have proposed void fraction correlations, e.g. Schrage et al. [5], Dowlati et al. [6] and Feenstra et al. [7]. For the two-phase multiplier, various investigators have applied the Lockhart and Martinelli method, [8], represented by a simple correlation designed by Chisholm and Laird [9]. Barmardouf and McNeil, [10], studied a range of available experimental data, mostly for pure fluids at atmospheric pressure, and concluded that the Feenstra et al. [7] void fraction correlation and the Ishihara et al. [11] two-phase multiplier correlation provided the best empirical information for the range of conditions likely to occur in a kettle reboiler.

Burnside et al., [12], reported that the one-dimensional model provided satisfactory predictions at low heat fluxes and suggested that a two-dimensional approach was necessary for heat fluxes greater than 20 kW/m^2. A study by McNeil et al. [13] has concluded that one-dimensional flows never occur and that the flow is two-dimensional with heat-flux dependent boundary conditions.

Several attempts have been made to model two-dimensional flows in a kettle reboiler with the two-fluid model. This model applies conservation equations of mass, momentum and energy to each phase. These are solved together with closure equations that define the interaction between the phases and between the phases and the tubes in the tube bundle. Edwards and Jensen [14] took this approach when knowledge of the interfacial momentum force was limited. They assumed a constant drag coefficient for the whole flow field. The value of the drag coefficient was altered to bring the predicted void fractions towards the experimental

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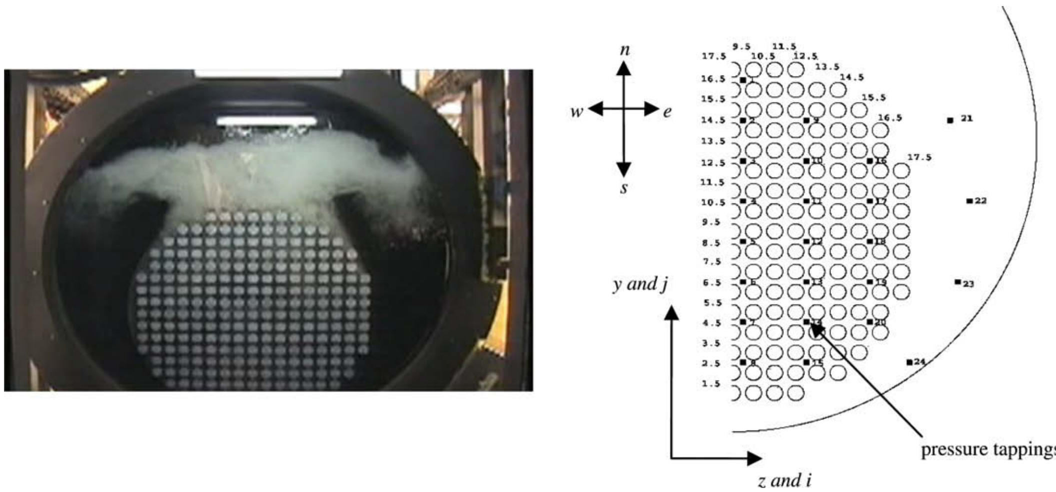

Fig. 1. Front view and tube layout of a kettle reboiler.

values. Convergence problems were encountered when the predicted void fractions were within 30% of the experimental values. Rahman et al. [15] also used the two-fluid approach. They were the first to model the interfacial drag force for a vertical two-phase flow across a horizontal tube bundle, using a drag coefficient developed from experimental data. They argued that only the liquid phase was in contact with the tubes in the tube bundle and that the resistance between the tube walls and the gas or vapour flow was therefore negligible. The drag coefficient was correlated as a power law function of the Reynolds number. Stosic and Stevanovic [16], Stevanovic et al. [17,18] and Pezo et al. [19] proposed two correlations for the drag coefficient, one for the bubbly flow regime and the other for the churn flow regime. They derived their coefficients from the air–water void fraction measurements reported by Dowlati et al. [20]. The details are given in Simovic et al. [21]. Barmardouf and McNeil [10] showed that their model does not reduce to the simple, one-dimensional model because the assumed wall force model, and consequently their drag coefficient, is not sufficiently accurate. The approach is therefore unlikely to predict two-dimensional flows with sufficient accuracy.

The failure of the two-fluid model to reproduce the observed phenomena in a kettle reboiler is caused by the drag and tube wall forces being poorly understood. Most of the local data available for understanding these forces has been obtained under one-dimensional flow conditions. Extrapolating this data to two dimensions is more consistent if a one-fluid approach is taken.

The one-fluid, or algebraic slip, model assumes that the two phases move in the same direction but with different velocities. This allows the empirical data for void fraction and tube wall force to be used directly. Burnside [22] modelled the two-dimensional flow in a kettle reboiler using the one-fluid model. This model has two deficiencies, it was applied to a rectangular tube bundle that is not commonly found in practice, and the boundary conditions imposed were for a static pool of liquid at the edge of the tube bundle. In attempting to use this model during this study, significant convergence problems were encountered when a more realistic tube bundle geometry was used. Also, McNeil et al. [13] have shown that the static liquid boundary condition is not always appropriate. The objective of this study is to extend the one-fluid model to allow more complex geometries to be used and to derive boundary conditions that are consistent with the empirical evidence.

2. Flow model

The fluid flowing across the horizontal tubes in a kettle reboiler has a liquid component with a density ρ_l and a vapour component with a density ρ_g. The vapour occupies α of the flow area, where α is known as the void fraction, and is found from the correlation of Feenstra et al. [7]. This correlation is based on the ratio of the gas to liquid velocity, or slip ratio. The gas velocity is therefore different in magnitude from the liquid velocity although they both move in the same direction.

The momentum equation for the vertical component of flow can be written as

$$\frac{\partial p}{\partial y} = \left(\frac{\partial p}{\partial y}\right)_G + \left(\frac{\partial p}{\partial y}\right)_A + \left(\frac{\partial p}{\partial y}\right)_F \tag{1}$$

where p is the pressure and y is the distance up through the tube bundle from the south boundary, Fig. 1. The first term on the right hand side of Eq. (1) is the gravitational pressure gradient. This can be calculated from

$$\left(\frac{\partial p}{\partial y}\right)_G = -\rho_{tp} g \tag{2}$$

where g is the acceleration due to gravity and ρ_{tp} is the two-phase density, given by

$$\rho_{tp} = \alpha\rho_g + (1-\alpha)\rho_l \tag{3}$$

The second term on the right hand side of Eq. (1) is the vertical component of the acceleration pressure gradient. This can be found from

$$\left(\frac{\partial p}{\partial y}\right)_A = -\left[\frac{\partial(\beta m_v^2)}{\partial y} + \frac{\partial(\beta m_v m_h)}{\partial z}\right] \tag{4}$$

where z is the distance from the tube bundle centre line to any position east of this, Fig. 1, m_v is the vertical component of mass flux, m_h is the horizontal component of mass flux and β is an effective momentum specific volume, defined by

$$\beta = \frac{x^2}{\alpha\rho_l} + \frac{(1-x)^2}{(1-\alpha)\rho_l} \tag{5}$$

in which x is the gas-mass fraction.

The last term on the right hand side of Eq. (1) is the vertical component of the frictional pressure gradient. This can be found from the force on the fluid by the tube walls. If n is the distance along the total velocity flow path, the force per unit volume on the flow by the tube walls is

$$\left(\frac{\partial p}{\partial n}\right)_F = \left(\frac{\partial p}{\partial n}\right)_{Flo} \phi_l^2 \tag{6}$$

where ϕ_l^2 is the two-phase multiplier, calculated from the correlation of Ishihara et al. [11], and the other term is the force per unit