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Numerical simulation of two-dimensional kettle reboiler shell side thermal–hydraulics with swell level and liquid mass inventory prediction

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ABSTRACT

Simulation and analyses of two-phase flows across tube bundles is important for design and safety analyses of various types of steam generators and kettle reboilers. The information about the shell side thermal–hydraulics in this thermal equipment should include the liquid and vapour two-phase flow velocity fields, the void fraction distribution, as well as the swell level position and the liquid mass inventory. The two-fluid model of boiling two-phase flow around tubes in the bundle is applied for the simulation of the kettle reboiler shell side thermal–hydraulics. The tube bundle is modelled as a porous medium. Transfer processes at the vapour–liquid interfaces and on the tube walls are predicted with closure laws. The model is numerically solved by the "in-house" CFD code. The applied modelling method is validated against measured data of pressure drops in refrigerant R113 and *n*-pentane two-phase flows across tube rows in the bundle of a thin slice kettle reboiler, which are available in the open literature. The swell level position on the shell side is calculated solely by solving of the two-phase flow governing equations and with the application of an appropriate closure law for the vapour–liquid drag force, which enables the prediction of the liquid separation due to gravity from the upward flowing two-phase mixture. This is an improvement on the thermal–hydraulic modelling and numerical simulation of the kettle reboiler since the previous numerical simulations from the open literature have been performed with a priori specified swell level position and arbitrary boundary conditions for the velocity (or pressure) and void fraction boundary conditions at the swell level. The prediction of the swell level position also enables the calculation of the liquid mass inventory on the shell side, which gives insight into the kettle reboiler operating conditions and is crucial for the reliable prediction of the tube bundle dry-out during incidents of liquid feeding stoppage. There is a one-to-one correspondence between the liquid mass inventory and the swell level position. The presented simulation method enables iterative prediction of the liquid mass inventory for the specified swell level position and vice versa. In addition, the correlations for the liquid–vapour interfacial drag coefficient, which have shown previously fairly good predictions in cases of water–steam and water–air two-phase flows, are extended for the general application to other fluids.

1. Introduction

The vapour–liquid two-phase flow on the shell side of the kettle reboiler has been a topic of research for decades with the aim of providing reliable design methods for this type of shell-and-tube heat exchangers with vapour generation [1]. In addition, results obtained at the scaled experimental facilities of the kettle reboilers improve the knowledge about the boiling two-phase flows across tube bundles, which is important for the design and safety of other vapour generators with boiling on the heated tubes in a bundle submerged in a liquid pool, such as horizontal steam generators in nuclear power plants [2,3] or fire-tube shell boilers [4]. The prediction of vapour void fraction distribution and the two-phase flow mass flux in the tube bundle and in the pool around the bundle is a crucial step in design and analysis of the kettle reboiler, the steam generator or the shell boiler operation. The void fraction distribution, for instance, determines the boiling heat transfer, the liquid inventory on the shell side and the swell level position [5]. Namely, high values of the void fraction can lead to the dry-out of the heated tubes and a reduction of the heat transfer area. The

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Nomenclature

Aq	area over which heat is transferred to fluid on the shell side
a	interfacial area concentration
C	parameter, Eq. (26)
C_D	drag coefficient
D	diameter
Dg	the drag group, Eq. (22)
F	force of interaction
f	Fanning friction factor
G	mass flux
g	acceleration of gravity force
h	enthalpy
M	volumetric mass source
n	concentration
p	pressure
q	volumetric heat rate
q_A	heat flux
T	temperature
t	time
$\vec{u}$ (u, v)	velocity
V_{in}	volume with the liquid source
V_q	control volume with heat transfer from tubes to fluid
X	the Martinelli parameter
x	Cartesian coordinate, static quality
y, z	Cartesian coordinates

Greek symbols

α	volume fraction
β	experimental parameter, Eq. (23)
Γ	evaporation/condensation mass transfer rate,
ζ	pressure loss coefficient
μ	dynamic viscosity
ρ	density
σ	surface tension
τ	relaxation time, shear stress
Φ	two-phase multiplier, Eqs. (25) and (26)
φ	vapour volume fraction in space occupied only by two-phase mixture

Subscripts and superscripts

B	bubble
c	condensation
e	evaporation
H_2O	water
i	interface
in	inlet
p	particle
sat	saturation
2	liquid
10	total two-phase flow is observed as liquid flow
1i	transfer between interface and liquid
2	vapour
21	interfacial transfer from vapour to liquid
3	tubes
31	interfacial transfer from tube walls to liquid
32	interfacial transfer from tube walls to vapour
$'$	saturated liquid
$''$	saturated vapour

two-phase mixture swell level depends on the void fraction distribution. A low swell level can uncover upper parts of the tube bundle, while a high swell level can cause droplets entrainment and carry out from the vapour generator, since the gravity separation in the vapour dome above the swell level is not effective under short distances [6]. The void fraction distribution also determines the shell side liquid mass inventory. A lower liquid mass inventory means that the vapour generator is more vulnerable to an incident caused by the stoppage of liquid inflow [7]. The two-phase flow mass flux across the bundle determines the heat transfer rate, while its high values can cause tube vibrations [8].

In recent years numerical models have been developed for the computer simulation and analyses of the kettle reboiler and steam generator shell side multidimensional thermal–hydraulics. Their application enables detailed insight into the two-phase flow filed, which is an important support in design and safety analyses, especially for those parameters and effects that cannot be measured either in experimental test facilities or in the real equipment. But, the main challenge of modelling two-phase flows is the development of the closure laws for the interface transfer processes, such as the gas phase and liquid momentum interface transfer due to drag force. One of the first models developed for the kettle reboiler shell side two-dimensional flow was presented in [9]. The two-fluid model of two-phase flow was applied, while the two-phase flow across the tube bundle was treated with the porous media approach. The importance of the vapour–liquid interface drag force modelling for the proper prediction of the void fraction and velocity fields in the two-phase flow across the tube bundle is emphasised. A parametric analysis of the influence of the interfacial drag force on the calculated flow field was performed by applying different values of the interfacial drag coefficient, with the assumption that the prescribed constant value of this coefficient can be uniformly applied within the whole flow field regardless of the two-phase flow pattern. This crude assumption was eliminated in [10] by developing a correlation for the interfacial drag coefficient between the gas and liquid phases in vertical two-phase flows across in-line and staggered horizontal tube bundles. The correlation is based on the Reynolds number (calculated with the mixture density and the relative velocity between the phases), and the porosity of the tube bundle. Qualitative comparisons of the numerical results with the available measured data were done, but without detailed numerical data validations. In both papers [9,10] the upper boundary of the calculation domain was a prescribed position of the two-phase mixture swell level. The swell level position was prescribed according to the assumed weir position and it was modelled with the constant pressure at this boundary. In [11] the two-fluid model was applied for the simulation of kettle reboiler two-phase flow experimental conditions presented in [5,12], with refrigerant R113 as the boiling fluid. The vapour–liquid interfacial drag force was modelled with the correlations that were previously applied to the steam–water two-phase flows across tube bundles in the horizontal steam generator [13,14]. Also, the boundary conditions for the liquid circulation at the prescribed swell level position as the upper boundary of the flow domain were proposed. A fairly good agreement between numerical and measured void fractions was achieved. The two-dimensional two-fluid model was also applied in [15] by Mc Neil et al. for the investigation of kettle reboiler shell side thermal–hydraulic. The methods for the prediction of interfacial drag coefficient presented by Rahman et al. in [10] and by Simovic et al. in [14] were analysed. The Rahman et al. [10] method showed a very good prediction for the air–water flow conditions across a tube bundle, while the