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Computational analysis of two-phase flow and heat transfer in parallel and counter flow double-pipe evaporators

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ABSTRACT

A computational study is carried out to compare the two-phase flow and heat transfer characteristics of a double-pipe evaporator operating under parallel and counter flow configurations for use in waste heat recovery and low grade geothermal applications. The heat exchanger considered uses low boiling point fluid FC-72 to recover thermal energy from water that is at a temperature greater than the boiling point of FC-72 through forced convective boiling. The simulations are carried out at steady state using the SST-k-ω Reynolds-Averaged-Navier-Stokes equations, and by employing the Eulerian two-fluid formulation for the region of the heat exchanger where multiphase flow with phase-change occurs. The net heat flux from the wall during nucleate boiling is evaluated using the Rensselaer Polytechnic Institute wall heat flux partitioning model with appropriate empirical and mechanistic closures for the underlying physical mechanisms such as ebullition characteristics. The present computational methodology is extensively validated by comparison of the predicted fluid and wall temperatures, local vapor fractions and heat transfer coefficients against experimental data in the literature. For the range of parameters considered, contrary to that generally expected in single phase double-pipe heat exchangers, under two-phase conditions (boiling), the parallel flow configuration is found to result in a greater thermal effectiveness as compared to the counter flow. This is observed irrespective of whether FC-72 flows in the tube or annulus, and can be attributed to the greater vapor generation relatively upstream and for most of the length of the heat exchanger during parallel flow conditions. For the heat exchanger considered, the net FC-72 vapor generation is also greater when FC-72 flows in the tube-side as compared to that in the annulus under both parallel and counter flow configurations, although with marginal variation in the overall heat transfer rates.

1. Introduction

Global realization for energy sustainability has led to extensive research and development in technologies for renewable energy, combined heat and power, trigeneration and heat recovery. One of the most promising retrofit strategies for reducing the overall energy consumption in industrial applications, including metal, plastics and food processing, cement manufacturing, data centres, drying, and air conditioning, is through recovery and further use of waste heat that is otherwise rejected from the process line. Depending on the temperature of the waste heat stream, the recovered energy is typically utilized for power generation, cooling (absorption refrigeration) or building thermal management [1]. Electricity generation from low grade waste heat streams (<120 °C), similar to low temperature geothermal or solar energy sources, is typically accomplished through organic Rankine power cycles that employ low boiling point hydrocarbons, such as FC-72 and HFE7100 [2–4] as working fluids. The energy recovery potential from such low grade heat is greatly dependent on the performance of recovery heat exchangers and evaporators employed. Double-pipe (concentric tube) heat exchangers have widespread use across several industries due to their advantages in flexibility of operation (evaporator/condenser), modular structure, ease of upscaling, low maintenance and suitability for a wide range of operating pressures and temperature differentials. Typical applications of such double-pipe evaporator and condensers are in waste heat recovery from gaseous and liquid streams, including heat recovery from internal combustion engine exhausts [5–7], refrigeration systems such as in dry-expansion evaporators of vapor

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Nomenclature

c_p	specific heat, J/kg-K
d	diameter of tube/annulus, m
d_{bw}	bubble departure diameter, m
f_{bw}	bubble departure frequency, Hz
G	inlet mass flux, kg/m^2-s
h	heat transfer coefficient, W/cm^2-K or specific enthalpy, J/kg
k	thermal conductivity, W/m-K
l	length of tube/annulus, m
m	mass flow rate, kg/s
p	operating pressure, Pa
q	heat flux, W/cm^2
T	temperature, K
ΔT_{sub}	degree of subcooling, °C
ΔT_{sup}	degree of superheat in water (with reference T_{sat} of FC-72), °C
ΔT_{sat}	degree of superheat, °C
x	length perpendicular to the axis of tube or annulus, m
z	length along the axis of tube or annulus, m

Symbols

α	volume fraction, dimensionless
ε	effectiveness dimensionless
ρ	density, kg/m^3
μ	dynamic viscosity, Pa-s
σ	surface tension, N/m

Subscripts

a	annulus-fluid
b	bubble
bulk	bulk fluid
C	liquid phase convection
E	evaporation
i,o	inner or outer
l	liquid phase
Q	quenching
t	tube-fluid
T	total
v	vapor phase
w	wall

compression plants [8], and solar thermal applications (double pass concentric tube collectors) [9].

Accurate prediction of the thermal-fluid dynamic behaviour inside the heat exchanger particularly when the working fluid undergoes phase change (boiling), is paramount for design optimization. The complexity in full scale modeling of flow boiling process accounting for the underlying mechanisms of liquid bubble interactions and bubble dynamics pose difficulties in reliable computational analysis for the design of such evaporative heat exchangers. The physical processes typically involve ebullition from numerous nucleation sites on the heat transfer surface and its interactions with the bulk flow, heat, mass and momentum exchange between the phases, bubble dynamics including coalescence or collapse and associated turbulence interactions. Most available literature on the analysis of double-pipe evaporators and condensers are based on experimental studies [8,10] that are constrained to the operating conditions and fluids employed for the studies, or approximated numerical analyses that assume axially one-dimensional flow, heat and mass transfer [11–14]. In a recent study, Parrales et al. [15] evaluated the suitability of 50 such empirical and mechanistic correlations of local vapor fraction, for the prediction of two phase flow behaviour in a vertical double-pipe (helical) evaporator. The comprehensive variety of correlations considered in their study [15] were classified by formulations based on: (i) homogenity (liquid and vapor travel at the same local velocity) with/without multipliers; (ii) explicit liquid-vapor slip velocity; (iii) drift-flux models accounting for non-uniform distribution of vapor fraction and local relative velocity; and (iv) other/-fully empirical. They found that only 7 of the 50 correlations considered, all based on the drift flux model, satisfactorily predicted the vapor fractions in the double-pipe evaporator when compared against experimental data. The difficulty in making simultaneous accurate measurements of the two-phase flow and thermal characteristics inside the heat exchanger and the sensitivity of the thermal-fluid dynamic behaviour to the enormous possible controlling fluid parameters and operating conditions limit the generalization of experimentally determined empirical models. Numerical analyses using CFD abate this difficulty and allow the governing equations to be solved for any specific geometry, operating condition or fluid, also with significantly fewer restrictions and assumptions than that inherent in approximate analytical or one-dimensional approaches [12,13]. However, few such studies are available in the literature predominantly due to the difficulty in accurately simulating the flow boiling process in the heat exchanger.

The recent development of Rensselaer-Polytechnic Institute (RPI) wall-boiling model [16] and its integration into the Eulerian two-fluid modeling framework [17] has been a significant milestone in facilitating macroscopic and large scale simulation of systems involving flow boiling phenomena. In the RPI model, the total heat flux from the surface during nucleate boiling is partitioned into liquid and vapor phase convection, quenching or transient conduction to the liquid occupying the void of a departed bubble, and latent heat transfer. During subcooled nucleate boiling, the contribution of vapor phase convection to the overall heat transfer is generally negligible and hence omitted. Empirical or mechanistic closures for the small scale processes that are evaluated based on the local flow field and thermal characteristics are integrated with the governing conservation equations and solved simultaneously in this approach. Since the development of the Eulerian-RPI multiphase approach, it is reported to have been successfully employed for the simulation of flow boiling processes in a variety of applications including tubular heat exchangers [18,19], nuclear reactor cooling systems [20,21] and electronics cooling [22,23].

In the present study, a computational analysis is carried out to compare the two-phase flow and thermal characteristics of a double-pipe evaporator operating under parallel or counter flow, for different mass flow rates and fluid inlet temperatures. Considering that some recent experimental studies [24,25] have identified the thermal effectiveness to be greater during parallel flow as compared to counter-flow (in contrast to single phase heat exchangers), in the present study, special emphasis is given to correlating the local thermal-fluid dynamic behavior obtained under the two configurations to the overall effectiveness of the double-pipe evaporator. As the simulations invariably involve two-phase flow with phase change on the cold-side of the evaporator, a series of rigorous tests are carried out *a priori* to establish the validity of the present Eulerian-RPI computational framework through comparison against experimental flow boiling data.