Heat transfer and exergy analysis of flow boiling evaporation in u-bend channel

T Jatau and T Bello-Ochende

1Department of Mechanical Engineering, University of Cape Town, Private Bag X3, Rondebosch, 7701, South Africa.

E-mail: tunde.bello-ochende@uct.ac.za

Abstract. This study presents, a numerical method used to evaluate the exergy analysis of flow boiling evaporation of R134a in a U-bend channel using entropy generation criterion which is concerned with the degradation of exergy during the process due to irreversibilities (entropy generation) contributed by heat transfer and pressure drop. The simulations were conducted with the heat flux of 15 kW/m$^2$, mass fluxes of 200-600 kg/m$^2$s of R134a at the saturation temperature of 15 $\degree$C. Three (3) different geometries sizes of U-bend channel’s diameter 6, 8 and 10 mm with the bend radius of 10.2 mm were utilized. The Volume of Fluid (VOF) multiphase flow formulation was used in Ansys Fluent. The results show that the entropy generation increases with increase in mass fluxes due to irreversibilities contributed by the heat transfer coefficient and pressure drop as mass fluxes increase. Based on the size of the U-bend channel, the entropy generation was found to increase as the diameter of the channel increases. The numerical results were compared with the data in the open literature and there was a good agreement.

1. Introduction

The two-phase flows in U-bend tube/channel evaporators are widely employed in refrigeration and air conditioning industry, power plant and petrochemical industries [1-2]. The two phase pressure drop and heat transfer coefficient are very important parameters to consider in the design of optimised evaporator. The amount of entropy generation is the quantitative measure of the quality level of energy transfer (exergy) which is as a result of irreversibilities contributed by heat transfer and pressure drop and these irreversibilities can lower the efficient performance of an evaporator.

A review of the existing research showed that a lot of investigations both experimental [3-6] and numerical [7-10] have been carried out to study the flow boiling evaporation in U-bend tube in order to improve the performance of the system. The prediction of two phase refrigerant pressure drop in U-bend channel which is of paramount importance in the design optimization have been carried out [11-14].

In order to optimise evaporators in refrigeration systems, entropy generation as a criterion during flow boiling of pure refrigerant and refrigerant oil mixture in a straight tube was used by Revellin and Bonjour [15]. Therefore, in this present paper, a numerical method is used to evaluate the exergy analysis of flow boiling evaporation in U-bend channel using entropy generation criterion which is concerned with the degradation of energy during a process due to irreversibilities. In this study, three (3) different sizes of channel’s diameters (6, 8 and 10 mm) with the same length and bend radius of 4 m and 10.2 mm respectively were utilized. This study focuses on heat transfer, total pressure drop and generation of entropy.
2. Methodology
The three dimensional computational domain of the geometry of U-bend tube was modelled in SpaceClaim and then imported into Ansys-Fluent. The grid generation of the model into discrete volumes was carried out using appropriate meshing parameters and techniques by ANSYS-meshing. The materials of the U-bend tube(copper) and fluid(R134a) were selected and the boundary conditions applied on the computational domain.

Prior to the two-phase flow calculation (transient simulation), a steady-state simulation was carried out to determine the flow field of one of the phases. Once the simulation was fully converged then both phases were introduced at the inlet. The two phase change model for mass and energy transfer was coupled through the development of User-Defined Function (UDF)

The volume of fluid (VOF) model was used for the numerical calculation of the two-phase flow. The piecewise linear interface calculation (PLIC) interface reconstruction method was used to track the geometry of the interface accurately. The pressure based solver was used with second order upwind scheme for momentum and energy equations. Pressure-implicit with splitting of operators (PISO) was considered as the pressure–velocity coupling method to maintain solution stability. Time steps of $10^{-5}$ s was chosen for the calculations. The simulations were conducted for geometries with different diameters; 6, 8 and 10mm.

To ensure the accuracy of the numerical results, an independent grid refinement test was conducted and validated using the work of Revellin and Bonjour [15] with good agreement as shown Figure 1

3. Results and discussion

3.1 Heat transfer coefficient and pressure drop
Figure 2(a) illustrate the relationship between the heat transfer coefficient and the mass fluxes of the evaporation of R134a in U-bend channel, the importance of the investigation of the effect of mass fluxes on the heat transfer coefficient is to understand vapour generation flow rate and absorption of heat by R134a along the U-bend channel. The vapour generation rate is faster at the mass flux of 200 kg/m$^2$s than that of the 600 kg/m$^2$s due to the higher wall temperature at the mass flux of 200 kg/m$^2$s. Hence, the wall temperature decreases with increase in mass fluxes as shown in Figure 2(b). The heat transfer coefficient increases as the wall temperature decreases with increase in mass fluxes as shown Figure 2(a) for three geometries of U-bend channel with different diameter sizes of 6, 8, and 10 mm. The heat transfer coefficient in the evaporator U-bend channel decreases because the convection heat transfer coefficient of the vapour phase of R134a is smaller compared with the liquid phase of R134a. Therefore, heat transfer coefficient is higher at the side of the channel with the saturated liquid phase of R134a than the side of tube with vapour phase of R134a. The liquid phase is usually occupy the lower side of the tube while the vapour phase occupies upper side due to differences in their densities.

Figure 2(c) shows the relationship between the pressure drop and mass fluxes(200 – 600 kg/m$^2$s) of flow boiling evaporation of R134a in U-bend channel for downward orientation flow. The pressure drop increases with increase in mass fluxes and decreases as the inner diameter of the channel increases. Therefore, the pressure drop of the channel with diameter of 6mm is the highest and channel with inner
diameter of 10mm is the lowest value. This is due to frictional pressure losses in the channel as the average density and viscosity of R134a liquid approaching the density and viscosity of R134a vapour. From Figure 6, it can also be seen that pressure drop increases with decrease in channel’s diameter as mass flux increases.

![Figure 2](image1)

**Figure 2.** (a) Heat transfer coefficient vs mass fluxes and (b) Wall temperature vs mass fluxes (c) Total pressure vs mass fluxes

### 3.2 Entropy generation

The amount of entropy generation is the quantitative measure of the quality level of energy transfer (exergy). The entropy generation has been plotted versus the mass fluxes for R-134a at a saturation temperature of 15°C for a heat flux of 15 kW/m² as shown Figure 3. In the flow boiling evaporation of R134a in the U-bend channel, the entropy generation increases with increase in mass fluxes due to irreversibilities contributed by heat transfer and pressure drop. An effective heat transfer and low pressure drop will result to low value of overall entropy generation which means there is low degradation of energy (high exergy) due to irreversibilities. Therefore the performance of the U-bend channel evaporator reduces as the entropy generation increases and the reverses is the case when the entropy generation decreases, the performance of the evaporator also tend to increase.

Based on the size of the U-bend channel, the entropy generation increases as the diameter of the channel increase. From the Figure 3, it can also be seen that the entropy generation increases as U-bend channel’s diameter size increase from 6 to 10 mm.

![Figure 3](image2)

**Figure 3.** Entropy generation vs mass fluxes

### 4. Conclusions

The numerical simulation was conducted to evaluate the exergy analysis of flow boiling evaporation of R134a in U-bend channel using entropy generation criterion which is concerned with the degradation of exergy during a process due to irreversibilities as result of heat transfer and pressure drop in the channel. The single phase of liquid R134a at the saturation temperature of 15 °C enters the channel at inlet and exit as vapour phase with mass fluxes 200-600 kg/m²s at the constant uniform heat flux of 15
kW/m² applied on the outer surface of the channel. The simulation was conducted for three (3) different U-bend circular channels with inner diameter of 6, 8 and 10 mm with the same bend radius of 10.2 mm.

The effect of mass fluxes on the heat transfer coefficient with respect to vapour generation and absorption of heat of the R134a along the U-bend channel show that the vapour generation rate is faster at the mass flux of 200 kg/m²s than that of the 600 kg/m²s due to the high wall temperature at lower mass flux of 200 kg/m²s. Hence, the wall temperature decreases with increase in mass fluxes. The heat transfer coefficient in the evaporator U-bend channel decreases because the convection heat transfer coefficient of the vapour phase of R134a is smaller compared with the liquid phase of R134a. Therefore, heat transfer coefficient is higher at the side of the channel with the saturated liquid phase of 134a than the side of tube with vapour phase of R134a. For the three (3) geometries of U-bend channel with different diameter sizes of 6, 8, and 10 mm, it was observed that the geometry of diameter size of 10 mm has the highest transfer coefficient followed by geometry of diameter size of 8 mm and then the geometry of diameter size of 6 mm.

In the term of pressure drop, the total pressure drop increases with increase in mass fluxes and decreases as the diameter of the channel increases. Therefore, the pressure drop of the channel with the diameter of 6 mm was found to be highest as compared to channel’s diameter of 8 and 10 mm respectively. This is due to frictional pressure losses in the channel as the average density and viscosity of R134a liquid approaching the density and viscosity of R134a vapour.

The entropy generation in the U-bend channel was found to increases with increase in mass fluxes due to irreversibilities contributed by heat transfer and pressure drop. The pressure drop contributed more to overall entropy generation than the heat transfer as mass fluxes increase. Based on the size of the U-bend channel, the entropy generation increases as the diameter of the channel increases from 6 to 10 mm. Therefore the performance of the U-bend channel evaporator reduces as the entropy generation increases and the reverses is the case when the entropy generation decreases, the performance of the evaporator also tend to increase.

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