**International Conference on Applied Energy 2019**
**Aug 12-15, 2019, Västerås, Sweden**
**Paper ID: 0185**

# INVESTIGATION OF ENTROPY GENERATION DURING CONDENSATION IN INCLINED SMOOTH TUBES

Adelaja, A. O.[1,2*], Omosehin O.S.[2], Dirker, J.[1], Meyer, J.P[1]

[1]Department of Mechanical and Aeronautical Engineering, University of Pretoria, Pretoria, 0002, South Africa

[2] Department of Mechanical Engineering, University of Lagos, Akoka, Yaba, 101017, Lagos, Nigeria (Corresponding Author)

## ABSTRACT

The design and optimization of heat exchange equipment for effective and efficient performance are imperative and need a thermodynamic analysis. In this study, the effects of mass flux, vapour quality, inclination angle, and flow pattern were investigated on the local entropy generation during the condensation of HFC 134a in an inclined smooth tube. Results showed that the effect of inclination on entropy generation was insignificant for high mass fluxes cum high quality and for Re ≥ $1.75\text{x}10^{5}$. For high mass fluxes, entropy generation decreased with quality but was unpredictable for low mass fluxes. 66.7% of the data for the gravity-independent flow and 87.5% of the data for gravity-dependent flow were found to have local minimum entropy generation number during upward and downward flows respectively.

**Keywords:** entropy generation number, condensation, inclination angle, flow pattern map, two-phase flow.

## NONMENCLATURE

| | |
|---|---|
| $c_p$ | Specific heat (J/kg.K) |
| d | Diameter (m) |
| $h_{fg}$ | Enthalpy of vaporization (J/kg) |
| $\dot{m}$ | Mass flow rate (kg/m$^2$s) |
| N | Entropy generation number (-) |
| P | Pressure (Pa) |
| $\dot{S}_{gen,Q}$ | Entropy generation rate due to heat transfer (W/K) |
| $\dot{S}_{gen,\Delta P}$ | Entropy generation rate due to pressure drop (W/K) |
| T | Temperature (K) |
| $T_0$ | Reference temperature (K) |
| x | Vapour quality (-) |
| *Symbols* | |
| $\beta$ | Inclination angle ($^o$) |
| $\Delta$ | difference |
| $\varepsilon$ | Void fraction (-) |
| $\rho_{tp}$ | Two-phase flow density (kg/m$^3$) |
| subscripts | |
| fric | friction |
| in | inlet |
| l | liquid |
| mom | momentum |
| out | outlet |
| Q | Heat transfer |
| sat | saturation |
| stat | static |
| v | vapour |
| w | wall |

## 1. INTRODUCTION

Entropy generation analysis of a heat exchange system provides an in-depth focus into complex physical mechanisms that occur during multiphase flow. It also isolates the possible irreversibilities that occur due to turbulence inherent in it as a result of friction and heat transfer.

A review of literature can be found in Ref. [1 - 3]. Nouri-Borujerdi [4] employed numerical solution of the second law of thermodynamics to optimize microchannel sizes in two-phase flow application. The result showed that decreasing aspect ratio (AR) decreased entropy generation by heat transfer but increased entropy generation by pressure drop. In addition, that the lowest entropy generation was favoured by higher AR when wall heat flux or vapour quality increased. Bermejo et al [5] optimized the design of microchannel evaporator for space electronic cooling by combining a steady-state three dimensional conduction model with thermohydraulic flow boiling model. They showed that the AR of 8.8 gave the optimum design. Other works on two-phase flow are analytical [6 - 7] and experimental [8] in approach.

In this present study, the effect of inclination angle, flow pattern, mass flux, and quality are investigated on the entropy generation in two-phase flow in an inclined heat exchange system.

## 2. EXPERIMENTAL PROCEDURE AND DATA REDUCTION STRATEGY

The present study was conducted at the test facility in the laboratories of the Department of Mechanical and Aeronautical Engineering, University of Pretoria, South Africa. The test set-up (Figure 1) allowed for double tube condensation heat transfer and pressure drop data to be collected over a wide range of operating conditions (Table 1). The setup comprised of three flow loops: the refrigerant, the cooling water, and the hot water loops. In the refrigerant loop, there were two high-pressure lines. The first line contained the pre, test and post condensers, while the second line contained the bypass condenser which was employed to assist in regulating the amount of refrigerant through the test condenser.

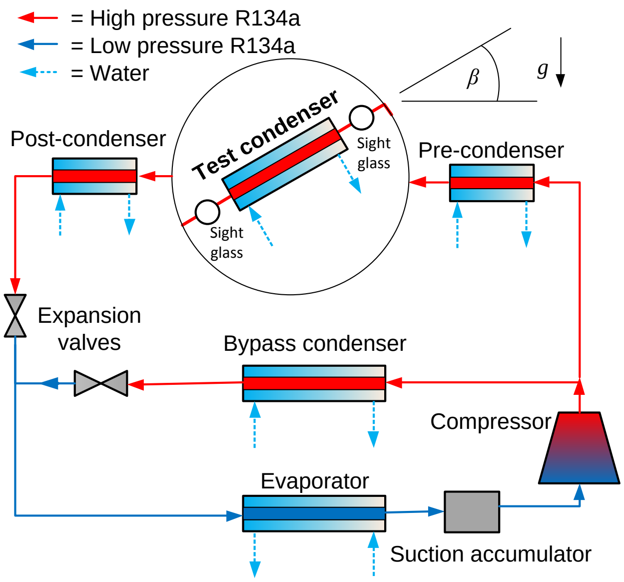

Fig 1: The schematic diagram of the test section

Table 1: Experimental variables and fluctuations

| Parameter | Range | Fluctuations |
|---|---|---|
| $T_{sat}$ [K] | 313.15 | ±0.6 |
| G [kg/m$^2$s] | 100 - 400 | ±5.0 |
| $x_m$ [-] | 25% - 75% | ±0.01 |
| $\beta$ [°] | -90° - +90° | ±0.1 |

The test section had a heat transfer length of 1.488 m and a differential pressure length of 1.704 m. It was a double pipe counterflow condenser constructed from hard drawn copper with water as a coolant in the annulus. The refrigerant vapour condensed inside the inner tube. The inner tube had an inner diameter of $d_i$ = 8.38 mm and an outer diameter of $d_o$ = 9.55 mm while the annulus had an outer diameter of 15.9 mm. The connections to the test condenser were made of flexible pressure hoses. These enabled the test section to rotate about two fixed hinges. To ensure that the flow through the test section was fully developed, a straight calming section, 50 diameters long was situated at the entrance. See Ref. [9, 10] for the full details.

## 3. ENTROPY GENERATION ANALYSIS

The entropy generation in the system is due to the combined effect of heat transfer and pressure drop of the two-phase flow passing through the test section. Entropy generation number is a dimensionless parameter employed in this study as follows:

$$N_{i,T} = N_{i,Q} + N_{i,\Delta P} \tag{1}$$

Where, the entropy generation number for the heat transfer and pressure drop, respectively, are presented as follows:

$$N_{i,Q} = \frac{\dot{S}_{gen,Q}}{\dot{m}c_p} \tag{2}$$

$$N_{i,\Delta P} = \frac{\dot{S}_{gen,\Delta P}}{\dot{m}c_p} \tag{3}$$

Where $\dot{S}_{gen,Q}$ and $\dot{S}_{gen,\Delta P}$ are the entropy generation rates for the heat transfer and pressure, respectively, and are expressed in equations (4 - 5). $\dot{m}$ and $c_p$ are the mass flow rate and specific heat capacity.

$$\dot{S}_{gen,Q} = \dot{m}h_{fg}(x_{in} - x_{out})\left(\frac{1}{T_{w,i}} - \frac{1}{T_{sat}}\right) \tag{4}$$

$$\dot{S}_{gen,\Delta P} = \frac{\dot{m}\Delta P_{fric}}{\rho_{tp}T_{sat}} \tag{5}$$

where

$$\rho_{tp} = \rho_v\varepsilon + \rho_l(1-\varepsilon) \tag{6}$$

$$\Delta P_{fric} = \Delta P_{test} - \Delta P_{stat} - \Delta P_{mom} \tag{7}$$

Here, $h_{fg}$ is the enthalpy of vaporisation while $x_{in}$, $x_{out}$, $T_{w,i}$ and $T_{sat}$ are inlet and outlet qualities, wall and saturation temperature, respectively. The two-phase density, $\rho_{tp}$, the liquid and vapour phase densities are $\rho_l$ and $\rho_v$, respectively while the void fraction is $\varepsilon$ [11]. $\Delta P_{fric}$, $\Delta P_{test}$, $\Delta P_{stat}$ and $\Delta P_{mom}$ are the pressure difference due to friction, measured test, static and momentum, respectively.

## 4. DISCUSSION OF RESULTS

In this section, the results of the effects of inclination angle, mean vapour quality, mass flux, Reynolds number and flow pattern on the local entropy generation number are presented. In Fig 2 is shown the result of entropy generation as a function of inclination angle for different mass fluxes for mean qualities of a) 25%, b) 50% and, c) 75%. Fig 2a shows that high mass flux and low vapour quality favour high entropy generation. The effect of inclination is significant at low quality as there is a significant difference between the maximum and minimum entropy generation number. Also, low quality favours downward flow as the local minimum $N_{i,T}$ occurs between -30° and -10° depending on the mass flux. In Fig 2b, for moderate quality, inclination effect is significant for G = 100 and 200 kg/m$^2$s. High mass fluxes support high entropy generation (G = 400 kg/m$^2$s) or low entropy generation (G = 300 kg/m$^2$s). The local minimum entropy generation occurs during inclination of +90° for high mass fluxes and between -15° and -10° for lower mass fluxes. Fig 2c indicates that for high quality, high mass fluxes have lower local entropy generation while lower mass fluxes have higher and respond significantly to inclination. Fig 3 shows the variation of entropy generation with two-phase Reynolds number for different inclination angles. It has been shown that entropy generation decreased with Reynolds number. It was also observed that inclination had little or no effect for high Reynolds number beyond 1.75x10$^5$. For low Reynolds number up to 1.5x10$^5$, the effect of inclination was significant. In this regime of flow, the vertically downward tube orientation in many cases had the worst entropy generation. This may be due to instabilities due to the formation of Taylor bubbles in the flow. The inclination angles of -30° - +5° happened to have the least entropy generation.

Fig 4 aims to categorize the data based on the flow pattern map [12] to see if there is a correlation between the local minimum entropy generation, the corresponding inclination angle, and flow pattern classification. It should be noted that the data for $x_m$ = 0.5, G = 300 kg/m$^2$s, is on the transition line. The thirteen inclination data were split between the regimes. For the purpose of this study, it was categorized as gravity-dependent regime. In that case out of the eight sets of data plotted on the gravity-dependent regime, 7 (87.5%) had the local minimum entropy generation occurring during the downward flow. For the gravity- independent regime, 2 out of 3 sets (66.7%) of data had the local minimum entropy generation occurring during the upward flow.

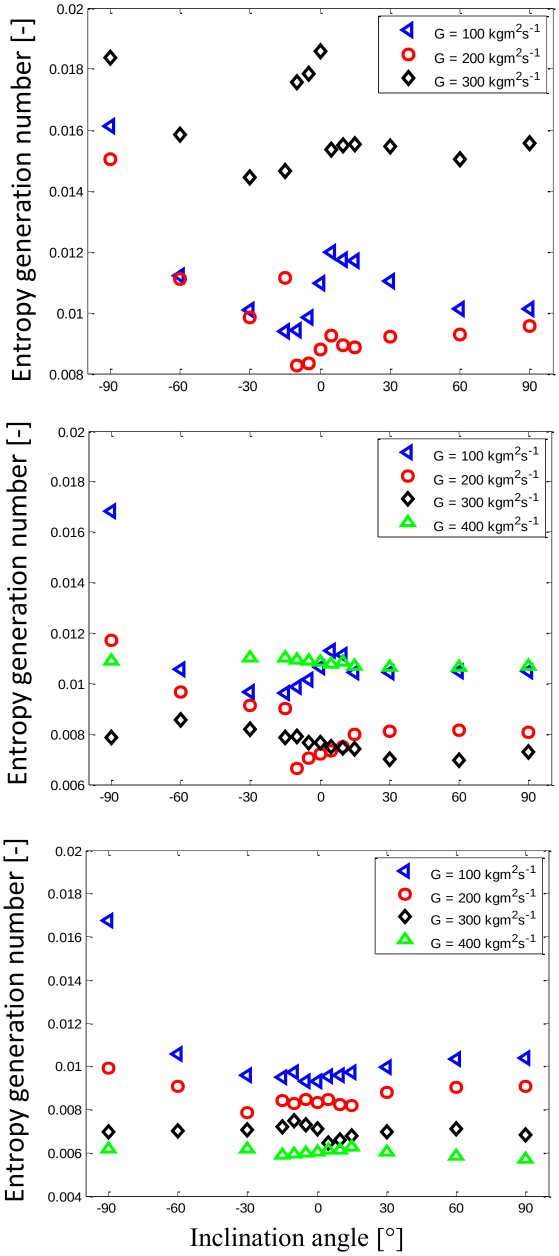

Fig. 2: Effect of inclination angle on entropy generation number for different mass fluxes for quality of a) 25%, b) 50% and, c) 75%.

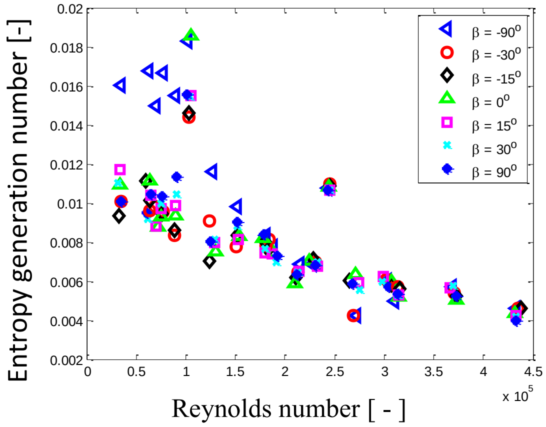

Fig. 3: Variation of entropy generation number with Reynolds number for different inclination angles.

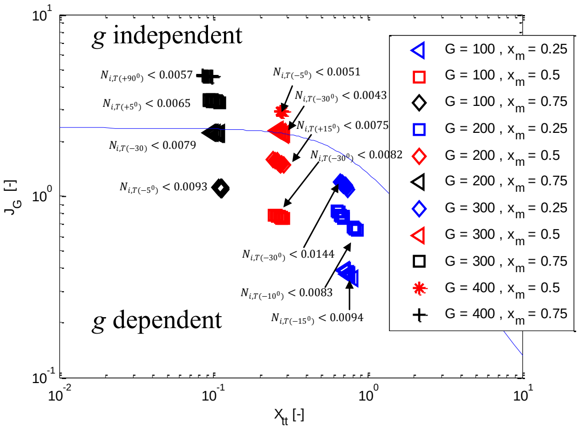

Fig. 4: The classification of entropy generation number on flow pattern map [12].

## 5. CONCLUSION

This study focuses on the effect of inclination angle, mass flux, quality, and flow pattern on the local entropy generation during flow condensation of HFC 134a in an inclined smooth double tube. The effect of inclination on entropy generation was found to be insignificant for high mass flux cum high quality and for Re of 1.75x$10^5$ and greater. Entropy generation decreased with quality for high mass fluxes but was unpredictable for lower. 66.7% of the entropy generation data for gravity-independent flow had their local minimum occurring during the upward orientation while 87.5% of the data for gravity-dependent flow had it during the downward flow.

## ACKNOWLEDGEMENT

The funding obtained from the NRF, TESP, Stellenbosch University/ University of Pretoria, SANERI/SANEDI, CSIR, EEDSM Hub and NAC is acknowledged and duly appreciated.

## REFERENCE

[1] Ries F, Li Y, Nishad K, Janicka J, Sadiki A. Entropy generation analysis and thermodynamic optimization of Jet Impingement cooling using eddy simulation. Entropy 2019; 129: 1 - 21.

[2] Awad MM. A review of entropy generation in microchannels. Adv. Mech. Eng. 2015; 7(12): 1–32.

[3] Bejan A. Thermodynamic optimization of geometry in engineering flow systems. Exergy Int. J. 2001; 4: 269 – 77.

[4] Nouri-Borujerdi A. Entropy generation in microchannels with two-phase flow. In: Proceedings of ASME 9th international conference on nanochannels, microchannels, and minichannels (ICNMM2011), Edmonton, AB, Canada, 19–22 June 2011, paper no. ICNMM2011-58210, 2011: 95–99.

[5] Bermejo P, Revellin R, Charnay R. Modeling of a microchannel evaporator for space electronics cooling: entropy generation minimization approach. Heat Transfer Eng. 2013; 34: 303–312.

[6] Revellin R, Lips S, Khandekar S, Bonjour J. Local entropy generation for saturated two-phase flow. Energy 2009; 34: 1113–1121.

[7] Collado FJ. The law of stable equilibrium and the entropy-based boiling curve for flow boiling. Energy 2005; 30: 807–19.

[8] Borkar GS, Lienhard JH, Trela M. A rapid hot-water depressurization experiment, EPRI 1977; NP-527.

[9] Meyer JP, Dirker J, Adelaja AO. Condensation heat transfer in smooth inclined tubes for R134a at different saturation temperatures. Int. J. Heat Mass Transf. 2014; 70: 515-525.

[10] Adelaja AO, Dirker J, Meyer JP. Experimental study of pressure drop during condensation in an inclined smooth tube at different saturation temperatures. Int. J. Heat Mass Transf. 2017; 105: 237-251.

[11] Bhagwat SM, Ghajar A.J. A flow pattern independent drift flow model based void fraction correlation for a wide range of gas-liquid two-phase flow, Int. J. Multiphase Flow 2014; 59: 188-205.

[12] Adelaja AO, Dirker J, Meyer JP. A condensation heat transfer correlation for inclined smooth tubes. In: Proceedings of the 12th International Heat Transfer, Fluid Mechanics and Thermodynamics Conference (HEFAT 2016 - 1570249348), Costa del Sol, Spain, 2016; 1- 6