Numerical investigations on the effect of slenderness ratio of matrix elements in cryogenic chill down process

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Abstract: Cryogenic fluids have many applications in space, medicine, preservation etc. The chill-down of cryogenic fluid transfer line is a complicated phenomenon occurring in most of the cryogenic systems. The cryogenic fluid transfer line, which is initially at room temperature, has to be cooled to the temperature of the cryogen as fast as possible. When the cryogenic fluid at liquid state passes along the line, transient heat transfer between the cryogen and the transfer line causes voracious evaporation of the liquid. This paper makes a contribution to the two-phase flow along a rectangular flow passage consisting of an array of elliptically shaped matrix elements. A simplified 2D model is considered and the problem is solved using ANSYS FLUENT. The present analysis aims to study the influence of the slenderness ratio of matrix elements on the heat transfer rate and chill down time. For a comparative study, matrix elements of slenderness ratios 5 and 10 are considered. Liquid nitrogen at 74K flows through the matrix. The material of the transfer line is assumed to be aluminium which is initially at room temperature. The influence of Reynolds numbers from 800 to 3000 on chill-down is also investigated.

1. INTRODUCTION

Analysis of two-phase flow problem is a complicated process. This paper makes a contribution detailed study of a two-phase flow problem along a porous matrix. Cryogenic chill down occurs in many cryogenic applications where cryogenic flow takes place. Cryogenic treatment of metals, superconductivity, space applications, gas liquefaction systems, cryopreservation, MRI, cryosurgery, chilling and freezing are some of the applications of cryogenics. As the cryogen in the liquid phase and at cryogenic temperature flows along a transfer line which is at room temperature, a phenomenon called chill-down occurs. Heat transfer occurs along the transfer line and cryogen causing vaporization which may cause pressure and flow surges in the fluid. As the flow progresses, steady state will be achieved when the transfer line is completely chilled to cryogenic temperature. A detailed study on the chill-down phenomenon is essential for designing transfer lines for reducing the chill down time.

Several basic experiments have been done by researchers to study the chill-down behavior of transfer lines. In 1960 Burke et al. [1] developed a chill-down model based on one-dimensional heat transfer through the pipe wall. In 1961 Graham et al. [2] correlated heat transfer coefficient and pressure drop with the Martinelli number. The prevalence of stratified flow during cryogenic chill-down was revealed Bronson et.al [3]. Chi et.al studied the different flow and heat transfer regimes along a pipe. Velat.et.al [4] contributed to the chill-down study with visual recording along a transparent pipe. Chi.et.al [5] proposed an empirical equation for predicting chill-down time. A correlation for the wall temperature during chill-down was proposed by Cross.et.al [6]. Chen.et.al [7] introduced a correlation for saturated boiling. Chen’s correlation was modified by Gungor et.al. [8]
and made applicable to sub-cooled boiling. Friction factor in cryogenic two-phase flow was suggested by Rogers [9] using Martinelli model. Sunil Kumar et.al [10] has done an experimental study on cryogenic feed line for investigating the effect of inlet source pressure and pressure surge on chill-down. The present study considers chill-down and heat transfer characteristics along a rectangular channel with elliptical shaped matrix elements arranged in staggered manner. The effect of slenderness ratio of mesh elements on the heat transfer is studied. The influence of Reynolds number on chill-down is also analyzed.

2. PROBLEM FORMULATION AND SOLUTION PROCEDURE

In the present work a two dimensional modeling of the given geometry is done in ANSYS FLUENT. From the literature the ability of CFD code ANSYS for solving phase change and heat transfer problems are identified. We have simulated an unsteady flow along a porous rectangular channel with heat interaction and multiphase transitions. The study aims to investigate the effect of slenderness ratio of matrix elements and Reynolds number on the heat transfer rate.

We have considered a rectangular 3D geometry consisting of an array of matrix elements staggered within the volume. Figure 1 indicates the geometry of considered channel. For simplicity of computation a corresponding 2D section is considered for modeling and simulation (Figure 2). Meshing and analysis of the present problem were done in ANSYS 14.5 WORKBENCH. Pressure based solver is used for the analysis as flow is assumed unsteady and incompressible. As two-phase transition occurs along the flow domain multiphase VOF model is used. Viscous model used is Realizable k-ε model with standard wall functions. SIMPLE (Semi-Implicit Method for Pressure Linked Equations) algorithm is considered. The boundary conditions are velocity inlet, pressure outlet, adiabatic wall at one side (since it is assumed insulated) and symmetric wall at other side. The initial flow temperature of the flow domain is set to 300 K and it is assumed to be filled with air. The matrix material considered is aluminum and the cryogenic fluid is liquid nitrogen at 74 K at atmospheric pressure. The variation of the properties of nitrogen with respect to temperature is considered as piece-wise polynomial. The effect of gravity on flow is neglected.

![3D geometry](image_url)

Figure 1: 3D geometry

Two different geometries are considered. The outer domain is fixed. The inner arrangement of matrix elements is varied on the basis of slenderness ratio. Slenderness ratio (SR) refers to the ratio of
lengths of major axis to minor axis of a given cross section. Slenderness ratio is varied by changing the length of major axis alone. The minor axis is fixed such that the flow area will not be reduced along the flow direction. Two different geometries are considered for matrix elements with slenderness ratios 5 and 10. As slenderness ratio of matrix elements increases, the porosity of the channel decreases. The heat transfer area will also be increased with increase in slenderness ratio. The effect of Reynolds number is also studied for Reynolds numbers ranging from 800 to 3000.

3. RESULTS AND DISCUSSION
In the present study the effect of slenderness ratio of matrix elements and Reynolds number on chill-down are investigated. Four different cases with Reynolds numbers 800, 1000, 2000, 3000 are simulated. All four flow conditions are considered for the geometries with SR5 and SR10. Since the flow cross sectional areas remain almost constant, the pressure drop variation is neglected. The effect of slenderness ratio of matrix elements on chill-down for Reynolds number 800 is primarily simulated. Matrix elements with geometries of SR5 and SR10 are compared for the given flow. Figure 5 indicates the contours of volume fraction of nitrogen along the channel with mesh elements of SR5 and correspondingly Figure 6 shows the contours of volume fraction of nitrogen along the channel with SR10. The contour of volume fraction of cryogen provides better understanding on the flow along the matrix elements. The flow pattern is an important parameter in analyzing chill-down process.
The temperature distribution of the flow domain is shown in Figure 7 and Figure 8. Detailed investigation on the contours will help us to understand the temperature changes along different sections from inlet for both cases with SR5 and SR10. From the time versus heat transfer rate plot it can be found that heat transfer coefficient is higher for channel with matrix elements of SR10. There is an increase in heat transfer rate by 3500 W/m²K for improved slenderness ratio. As flow rate increases heat transfer rate increases. Studies were conducted for cases with Reynolds numbers ranging from 800 to 3000. The figures 9 and 10 refer to distribution of nitrogen along the channel for both cases with SR5 and SR10 at Reynolds number 3000. Comparison of contours from figures 6 and 10 gives us a physical idea of nitrogen distribution at various flow times for the same geometrical configuration with SR10 and at different flow conditions with Reynolds numbers 800 and 3000.
Figure 7: Contours of temperature for SR5 and Re 800

Figure 8: Contours of temperature for SR10 and Re 800

Figure 9: Volume fraction contours of nitrogen for SR5 and Re 3000
Figure 12 shows that, for the geometry with slenderness ratio 5, the maximum heat transfer coefficient is when the Reynolds number is 800 and the value is about 14500 W/m²K. And as Reynolds number increases heat transfer coefficient decreases. The variation of Reynolds number from 800 to 3000 has decreased the maximum heat transfer coefficient by about 10,000 W/m²K. From figure 12 and figure 13, it can be understood that increase in slenderness ratio of mesh elements have contributed to improved heat transfer rate. But for higher flow velocities the effect of slenderness ratio is less. The heat transfer rate for the flow condition with Reynolds number 3000 is approximately 4500 W/m²K. Even though the heat transfer coefficient will have a maximum value for lower Reynolds numbers for a particular geometry it can be seen that for lower flow time the heat transfer coefficient is higher for higher Reynolds numbers. This is due to the faster chill-down of matrix elements for higher flow rates. The temperature gradient will be less at higher flow times for higher Reynolds numbers.
4. CONCLUSION
The present study gives an understanding of two-phase flow and heat transfer characteristics along a porous channel with staggered matrix elements of elliptical cross section. The influence of slenderness ratio of matrix elements and Reynolds number of the fluid on chill-down is discussed. As the porosity of the flow channel is varied by varying slenderness ratio alone, the flow stream cross sectional area is kept constant, thereby improving chill-down rate without decrease in pressure drop. The results obtained infer that, by increasing the slenderness ratio from 5 to 10, the heat transfer coefficient is increased by 3500 W/m²K for a flow Reynolds number of 3000. The increase in heat transfer coefficient for matrix elements with higher slenderness ratio has decreased the chill-down time which saves the amount of liquid nitrogen requirement for chill down.
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