Analysis of Vertical Thermosyphon Reboiler using CFD

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Abstract

The design of Vertical Thermosyphon Reboiler systems is complex involving many parameters associated with flow and heat transfer. While experimental analysis is expensive owing to a lot of parameters influencing the performance, numerical simulations get very complex as it involves multiphase flow with heat, mass and momentum transfer interactions. CFD proves to be a useful tool in analysis of such systems. CFD simulations were performed on a single tube of a Vertical Thermosyphon Reboiler systems modelled axis-symmetrically using STAR CCM+ package. The influence of flow parameters on performance of reboiler was analyzed by measuring cross sectional averaged volume fraction of vapourin a heated vertical tube for different wall temperatures, inlet velocities and operating pressures. For water entering a VTR tube under subcooled conditions at 80 °C, vapour generation is most sensitive to flow velocities for wall temperatures at 130°C. For wall temperatures at and greater than 120°C increase in velocity results in increased vapour generation while for wall temperatures less than 120°C increase in velocity results in decrease in vapour generation.

Keywords: *Vertical Thermosyphon Reboiler, CFD, Volume fraction of vapour, Wall temperature*

1.0 Introduction

Natural circulation systems such as Vertical Thermosyphon Reboilers (VTR) are widely used in petroleum, chemical, petrochemical and power plant industries. VTRs are the most widely used class of reboilers in process industries. These have low operating costs, easy installation and come with compact size dimensions for a given duty [1]. VTRs operate on natural circulation created by density difference between column bottoms liquid at the reboiler inlet and the reboiler outlet liquid-vapor

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mixture. Convective movement of the liquid starts as the liquid gets heated and causes it to expand. Hot liquid at the top becomes less dense and hence more buoyant than the cooler liquid present at the bottom. Heated liquid entering inside the tube rises upwards in the system and gets replaced by cooler liquid returning downwards by the virtue of gravity.Thermosyphon reboiler systems have been subjected to analysis for many decades. But the literature related to VTR is limited to numerical simulation till date as very little work has been done on simulations using CFD. Several attempts have been made to predict the performance of thermosyphon reboilers experimentally, and numericalmodelshave been developed for reboilers and similar systems. Authors analyzed instabilities involved in two phase flow in a VTR that are operated at sub-atmospheric pressures [2].S Arneth et al. [3]performed experimental and theoretical study to identify operational characteristics of thermosyphon reboilers. Responses of reboiler operation to variation of operating pressure, driving temperature difference and the driving liquid head in the inlet line in a VTR were investigated. A simple model was developed to explain the effect of parameters involved. VTR operating under vacuum was modelled using data obtained from experiments conducted by A Alane et al. [4]. This study looked at coupled problem to obtain better estimates of the heat transfer coefficients for the condensing steam in the shell and the heated process fluid in the tubes of a thermosyphon under steady state. M. Shamsuzzoha et al. [5] have performed analysis to study incipience of nucleate boiling for a VTR. The maximum value of superheat found around the onset of boiling was derived from distributions of wall-temperature and correlated with submergence, physical properties of working liquids and heat flux. An article published by M D Hagan et al. [6] gives an understanding of limitations of heat flux on design of reboilers. The article suggests that it is good to avoid transition to film boiling in order to establish better control in operation and reduce capital and operating costs of the reboiler.The existing work on VTRs is either experimental or numerical modelling reporting only the performance of thermosyphon reboilers under a set of specific conditions while very little work has been done on parametric evaluation of thermosyphon performance.There exists a gap in using these results in case of varying scales, different working fluids, varying geometries and operating conditions.While experimental analysis is expensive owing to a lot of parameters influencing the performance, numerical simulations get very complex as it involves multiphase flow with heat, mass and momentum transfer interactions. Performance of VTR tubes is not only influenced by heat transfer parameters like heat flux, and temperature differences but are also highly influenced by flow characteristics also. Hence CFD plays a significant role in analysis of systems like VTR that involve multiphase flow. However, there is no work reported on analysis of heat transfer characteristics of VTR using CFD.

In the present work generation of vapors inside a thermosyphon reboiler tube was simulated using CFD package STAR- CCM+ 9.04.011 as a simulation tool to measure axial variations of volume fraction of vapors, temperature of liquid, driving temperature differences inside the tube and study the effects of flow velocities, varying wall temperatures, operating pressure and inlet sub cooling. The performance of VTRs is measured in terms of cross-sectional average of volume fraction of vapour along the length of vertical tube. Influence of parameters like wall temperature, fluid inlet velocities and operating pressures on inception of boiling and vapour generated also have been observed with water as the working fluid.

2.0 System Description

The model considered for analysis consists of a single tube of VTR.Water is used as the working fluid for the study. Preheated water close to its saturation enters the heated tube. Water begins to boil when temperature of the wall exceeds the saturation temperature of water markingthe point inception of boiling (IB) when small bubbles begin to form. Further the inception points the degree of subcooling decreases and the volume of vapour begins to increase. This position along the length of the tube is determined as point of Net Vapour Generation (NVG). Beyond the point of NVG, along the axial length of the tube, volume fraction of vapour continues to increase, more and more bubbles detach from the wall and enter the liquid stream. The heat transfer interactions occur between bubbles and liquid owing to condensation of bubbles by losing heat to the liquid.

This work involves CFD simulation of boiling heat transfer in the reboiler tube using STAR CCM + package with specific objectives of measuring the exact point of inception of boiling and point of NVG. For the purpose of analysis, the vertical tube is divided into heating zone where sensible heat gets added to the fluid and the evaporation zone where vapors are generated and carried up the tube. Volume fraction of vapour, inception of boiling and NVG in the tube are important parameters to measure performance of a reboiler. This analysis is useful in optimizing the boiling of subcooled liquid inside the tube.

3.0 Simulation of Reboiler

Simulation of reboiler tube for boiling heat transfer is performed under a sequence of steps involving creation of geometry, generation of mesh, setting up physics, processing and post processing.

3.1 Creation of geometry and meshing

The basic geometry is a tube of 15.4 mm diameter and heated length of 2 m. To allow some flow development between the inlet and the heated section, a short unheated leader has been added. Similarly, in order to ensure that the outlet conditions in this developing flow do not influence the end of the heated section, a short trailer has also been added. The tube was modelled in cylindrical 2D axisymmetric volume mesh with 115 cells axially, 20 cells radially to result in 2300 cells, 4465 faces and 2436 vertices. These meshing parameters were verified for analysis of refinement in the studies conducted by E Končar et al.[7] as they are an agreeable tradeoff between computational effort and numerical accuracy.

3.2 Physics of the system and methodology

The system is modelled for boiling at the wall, departure of vapour bubbles from the wall, condensation of few of the vapour bubbles inside the subcooled liquid, transport of vapor bubbles downstream the tube along with the liquid and interaction of liquid and vapor inside the tube using Eulerian Multiphase model.Nucleation Site Number Densityand Departure Diameter are chosen as they are applicable for water boiling under a wide range of pressures [8-9]. Continuous Phase Nusselt Number is calculated using the Ranz-Marshall correlation which in turn is used to calculate the heat transfer coefficient for the heat transfer from the bulk water to the bubble interface [10]. The Disperse Phase Nusselt Number is used when calculating the heat transfer coefficient for the heat transfer from the bubble interface to the bulk steam [11]. Tomiyama model is used for modeling bubbly flows. Drag reduction has not been accounted as it is insignificant for small spherical bubbles hence has not been accounted [12]. The Turbulent Dispersion Force setting is important for wall boiling calculations in the presence of condensation because it treats the differencing of rapidly changing volume fraction gradients more accurately. The Interaction Length Scale is based on the bubble size predicted by the S-Gamma model [13-14].

3.3 Simulation Cases and parametric evaluation

Simulation cases were set up in three different cases to study the (i) Influence of wall temperatures (ii) Influence of flow velocities and (iii)

Influence of operating pressures on generation of vapour inside the reboiler tube.

3.3.1 Influence of wall temperature vapour generation

Simulations studies were carried outwith water as the working fluid entering the tube under subcooled conditions at T_{in} =80°C. Cases were set up for eight wall temperature conditions varying between 90 ℃ and 180 ℃ .These cases were studied for threedifferent velocities between v = 1- 2 m/s.

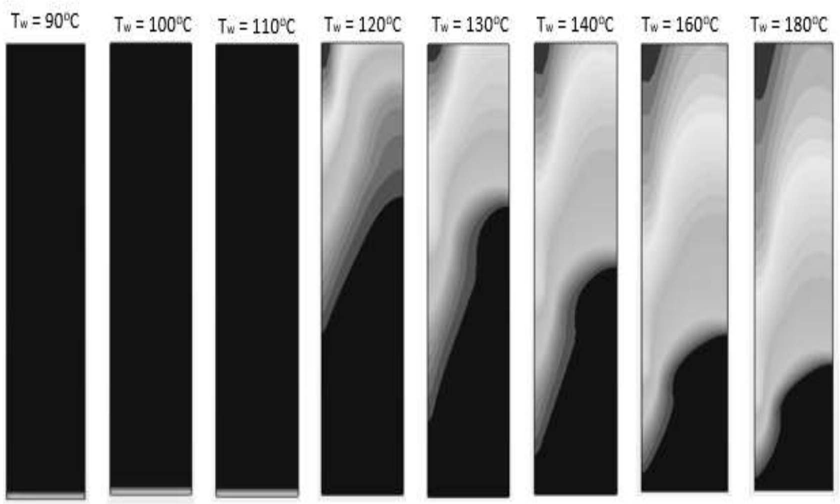

Fig. 1. Increasing wall temperature at $v = 1\,m/s$, T_{in} =80°C

For wall temperature increasing from $T_w = 120$ ℃ to 160 ℃for velocities in the range v =1 m/s to v =2 m/s, there was a significant increase in vapour generation and decrease in heating zone while there was no significant change in these factors observed between wall temperatures $T_w = 160$ ℃ and 180 ℃ (Fig.1 and2). This is probably because of onset of transition from nucleate boiling to film boiling. For wall temperatures ranging between $T_w = 90$ ℃ and 110 ℃ no vapour generations occurred(Fig. 1). This is acceptable as the heat supplied through the wall in these three cases is insufficient to cause saturation and initiate boiling. But these cases show a very small amount of vapour formed at the inlet and vapour generation subsides downstream the length of the tube. However, simulation with wall temperatures ranging between $T_w = 120$ ℃ to 160 ℃did not show any such vaporization at the entrance of the tube. Further investigations are needed to be carried out in order to explain this behavior of boiling at the tube entry.

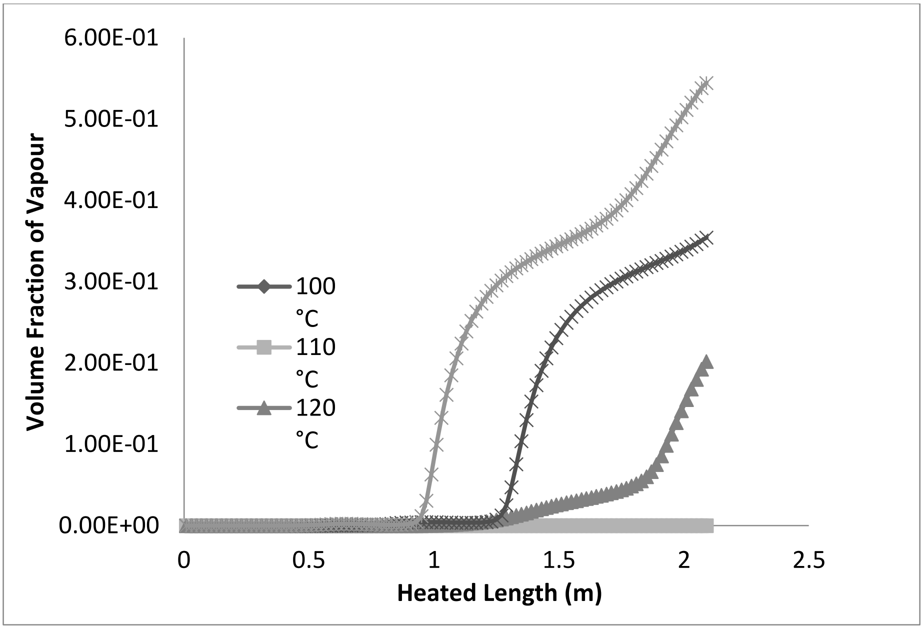

Fig. 2. Effect of wall temperature for $v = 1\,m/s$, T_{in} =80°C

3.3.2 Influence of flow velocity on vapour generation

Influence of flow velocity on vapour generation was studied by setting up simulation cases with velocities in the range $v = 1 - 2.5\ \ m/s$. These cases were set up for wall temperatures between $T_w = 120$ ℃ to 140 ℃ with water entering the tube at 80 ℃ under subcooled conditions at atmospheric pressure. Vapour volume fractions at different inlet velocities of water flowing through the tube were measured (Fig. 3). In the case of flow with $\Delta T = 40$℃, increase in velocity shows increase in heating zone and decrease in NVG as plotted in Fig. 4. This means inception of boiling is getting higher and higher inside the tube and NVG reducing with increasing inlet velocities. This behavior is different from what is expected as increase in velocities result in increasing turbulence, increase in heat transfer coefficients and hence increase in vapour generation. The deviation from expected behavior is probably because of generation of superheated vapor. However further investigations are to be conducted to prove this hypothesis.

In case of $\Delta T = 50$℃ and $\Delta T = 60$℃the pattern observed is slightly different from that of$\Delta T = 40$℃. With increase in velocities, inception of boiling gets higher and higher inside the tube but there is increase in vapor generation (Fig. 5 and 6).

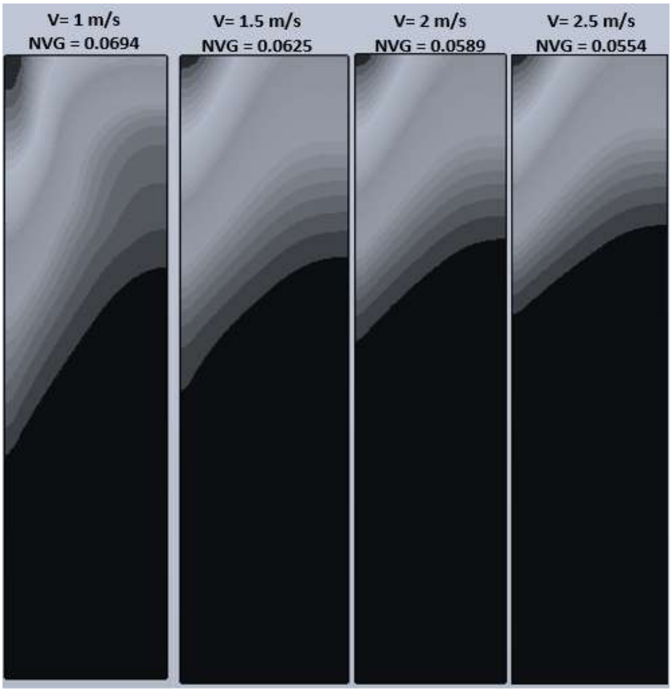

Fig. 3. Vapour volume fraction for varying velocities for $T_w = 120$ ℃

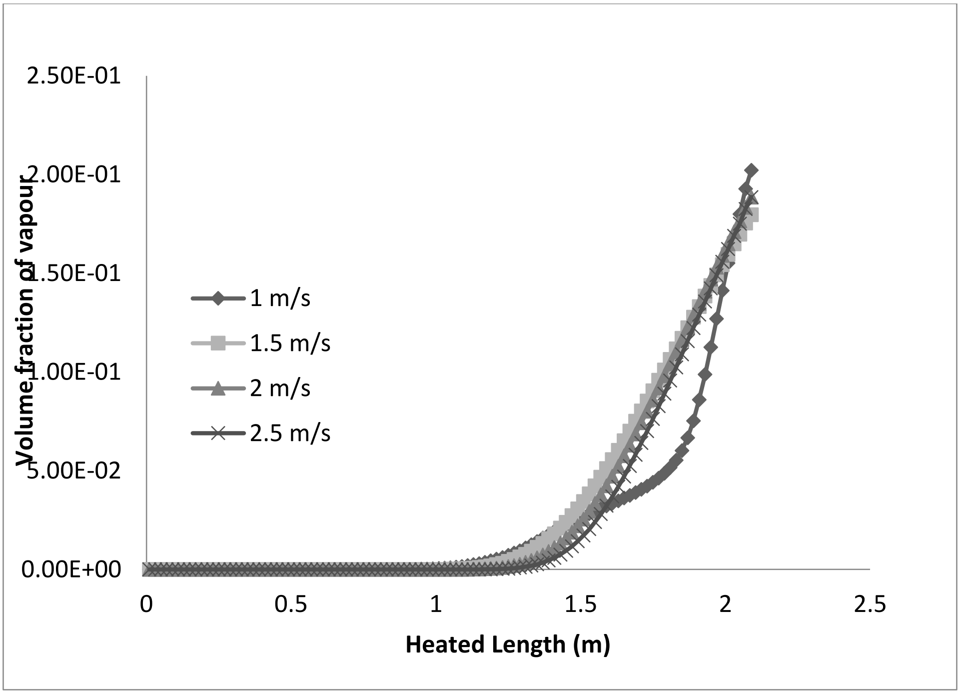

Fig. 4. Effect of velocity on vapour volume fraction for$T_w = 120$ ℃

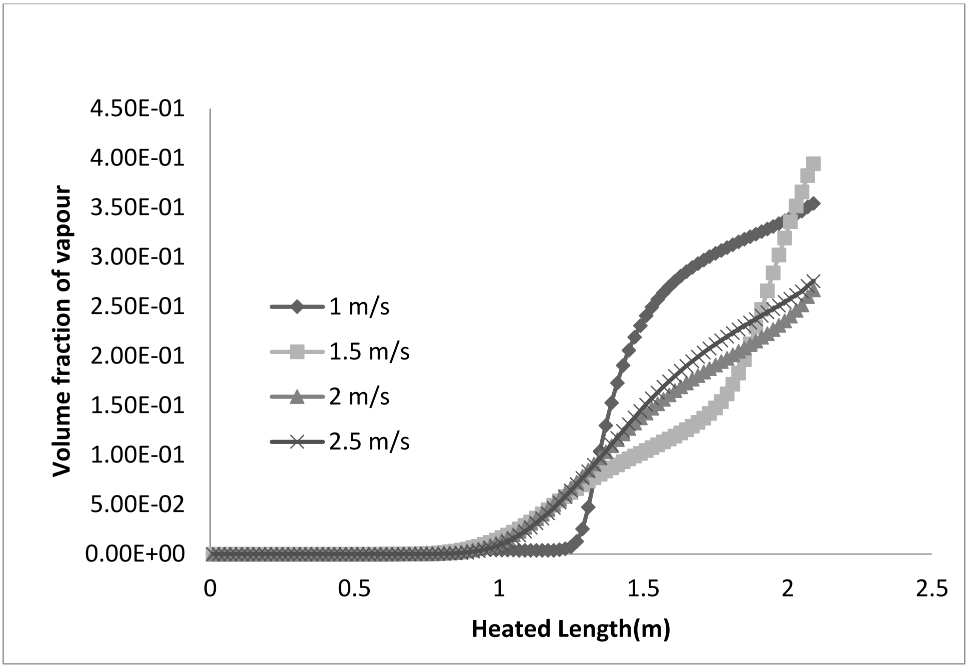

Fig. 5. Effect of velocity on vapour volume fraction for $T_w = 130$ ℃

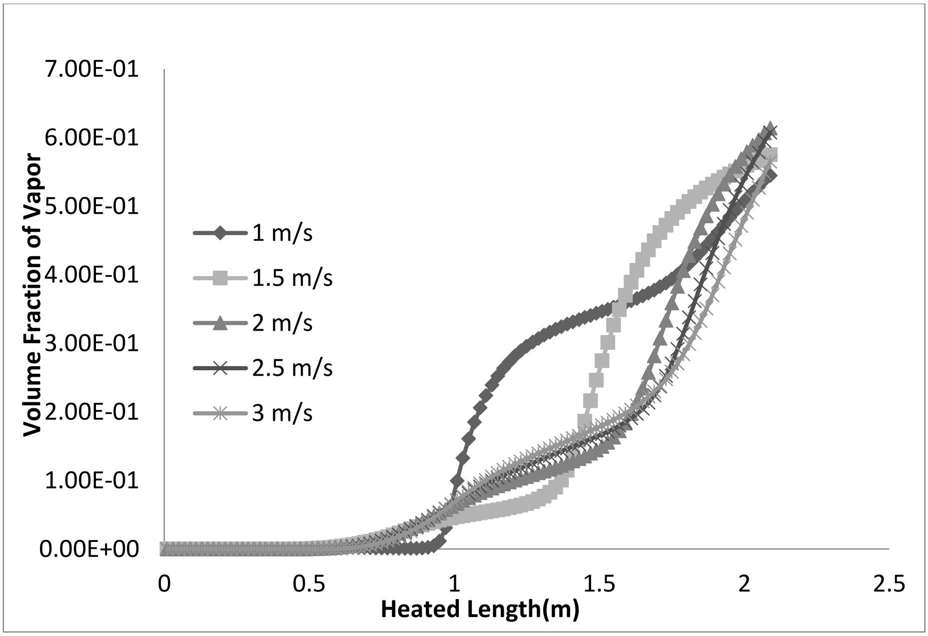

Fig. 6. Effect of velocity on vapour volume fraction for $T_w = 140$ ℃

3.3.3 Influence of operating pressure on volume fraction of vapour

Simulations were carried out to study the effect of operating pressures on vapour generation.

Simulations were run at three different operating pressures in the range 1-3 bar on water entering the tube at subcooled conditions at 80°C, velocity$v = 1\,m/s$ and boiling inside the tube with wall temperature 140 °C. Simulations runs with increasing operating pressure show that there is significant increase in vapour generated. Although the length of heating zone decreases with increasing operating pressures the impact is not considerably significant. This behavior is as shown in Fig. 7and 8.

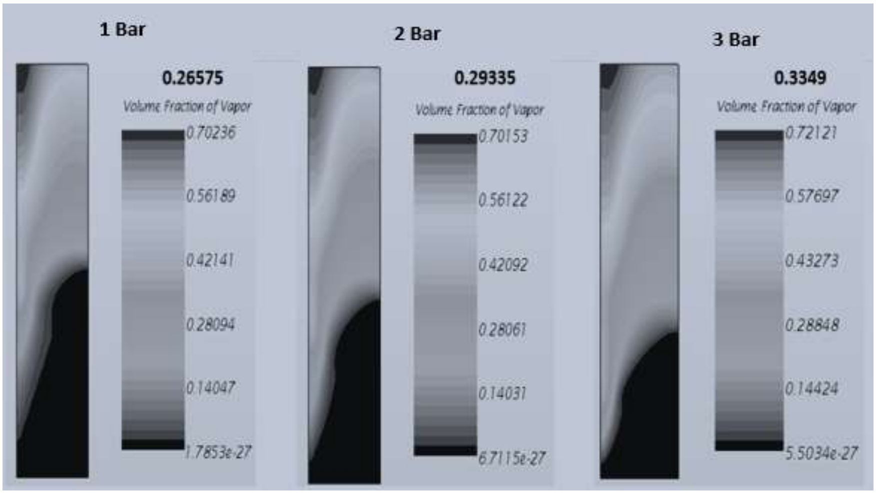

Fig.7. Influence of operating pressure on volume fraction of vapour

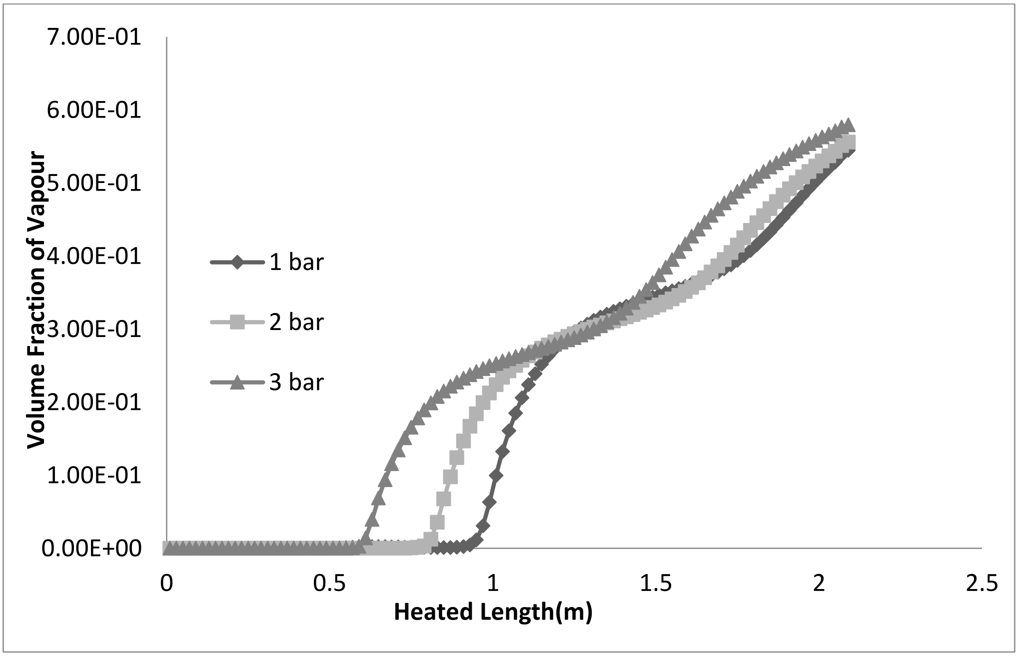

Fig. 8. Influence of operating pressure

4.0 Conclusion

A typical case of VTR operation with water entering a tube under subcooled conditions at temperature 80 ℃ was studied for varying wall temperatures, inlet velocities and operating pressures and the following conclusions are drawn.

- Minimum wall temperature required for inception of boiling for water entering at 80 ℃ and 1 bar pressure corresponds to $\Delta T = 40$℃ at inlet. Maximum wall temperature may go up to $T_w = 160$℃ as beyond that further increase in wall temperature does not result in significant increase in vapour generation.For wall temperature increasing from $T_w = 120$ ℃ to 160 ℃ there was a significant increase in vapour generation and decrease in heating zone.
- Although the physical conditions are not suitable for vapor generation at the beginning of the tube, boiling was observed for lower values of ΔTwhile this effect did not appear for$\Delta T \geq 40$℃ . This behavior needs further investigation.
- Simulations run with $\Delta T = 50$℃ were identified to be the most sensitive to flow velocity changes. It is favorable to operate reboiler with higher inlet velocities only for $\Delta T > 40$℃ as for $\Delta T < 40$℃ with increasing flowvelocities vapour generation reduces. Increasingvapour generation is seen in the range of inlet temperature differences between 40℃ and 60℃.
- Increase in operating pressure causes reduction in length of heating zone and vapour generation increases. Thus, it is favorable to operate reboilers at higher pressures.

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