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Investigation of Ring Type Spacer Effects on Performance of Heat Transfer and Flow Behaviour of Supercritical R-134a Flow using CFD in an Annular Channel

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Abstract: *Investigation of ring type spacer effects on performance of heat transfer and flow behaviour of R-134a flow at supercritical pressure, using CFD in an annular channel has been carried out. ANSYS Fluent has been used for simulation and turbulent model used in present study is SST k-ω. Present investigation is carried out at supercritical pressure 4.5MPa using fluid as R-134a.The objective is to focus the flow behaviour and thermal characteristics due to ring type spacer used for study. Pressure, velocity, temperature at wall and performance of heat transfer & corresponding mechanism in an annular channel have beenanalysed in detail. The results show that the wall temperature sharply reduced and the local heat transfer greatly enhanced at the location of spacer due to the flow area reduction. Due to spacer as flow obstruction, the static pressure is decreased and the velocity is greatly increased at spacer end. Comparison between CFD result for the ratio of coefficient of heat transfer for blockage ratio 0.3 and experimental data along with correlations given by several researchers at pressure of supercritical condition has been performed. The results of the ratio of coefficient of heat transfer (CHT/CHT*) is found in good agreement with the experimental data. The ratio of CHT without spacer annular channel is used to analysis the ratio of CHT with spacer in downstream.*

Keywords: Ratio of coefficient of heat transfer, supercritical R-134a, annular channel with spacer, CFD.

I. INTRODUCTION

Spacer grid is an important part in the assembly of nuclear fuel rod and it is used for maintaining suitable gap of fuel rods. It allows the coolant to perform its function properly. Functions of spacer grid in nuclear fuel rod bundle are to help in mixing enhancement between sub channels and provide support to the fuel rods in a bundle. It is observed that there are significant effects of spacer grid on fluid flow behaviour and performance of heat transfer of coolant inside sub channels. The investigation of flow characteristics to spacer downstream is also important in design of spacer grid. As one of the Generation-IV reactor, the supercritical pressure water cooled reactor (SCWR) has benefits of greater thermal efficiency, compact structure and simpler. Use of spacer grid is an efficient way to decrease the fuel rod temperature hence the design of supercritical water cooled reactor aim to reduce the fuel rod surface temperature to confirm the safety of nuclear fuel rod bundle. The increase in velocity of flow and the turbulence are due to the blockage in flow of the spacer grid are the main cause of the enhancement of heat transfer at spacer grid.

This paper shows an investigation of ring type spacer effects on flow characteristics and heat transfer of supercritical R-134a flow in an annular channel using CFD. ANSYS Fluent has been used for simulation and SST k-ω turbulence model has been used for turbulence simulation. In present study, spacers of two blockage ratios 0.3 and 0.38 have been used for analysis at supercritical pressure.

II. LITERATURE REVIEW

The investigation of spacer effects on performance of heat transfer and flow behaviour is important in nuclear reactor fuel rod bundle for the safety analysis. Numbers of studies have been conducted for pressures at subcritical and supercritical condition to analyse the effects of spacer grid. Analysis of dispersed flow at post critical heat flux was performed in single phase flow(Cluss and Junior, 1978).

Herer (1991) observed the intensity of turbulence and velocity through experiment using laser Doppler velocimetry for downward of a split-vane.

Yang and Chung (1998) analysed the intensities of axial turbulence for split-vane. Heat transfer in single phase subcritical pressure, the Nu is maximum at flow obstruction, for flow in bundle and the reduction in enhancement of heat transfer is exponential in downstream (Holloway et al., 2004; Yao et al.,1982)of spacer.

Caraghiauret al.(2009) reported that the details of geometry and location of spacer in fuel rod bundle cross section provide significant effects on the flow structure and rate of heat transfer.

Miller et al.(2013) worked for 7 x 7 pressurized water reactor bundle for prediction of heat transfer performance and superheated steam used as fluid. They proposed correlations which consider the blockage ratio effect and axial distance downstream from the spacer grid.

Guet al.(2016) performed an investigation through experiment for 2 x 2 fuel rod bundle with wire wraps, using single phase water at supercritical pressure. The wire wraps improve the mixing of fluid flow and increase the heat transfer.

Tanase and Groeneveld(2015) experimentally investigated the heat transfer performance due to flow obstructions in heated tube for fluid R-134a.They also proposed a correlation for heat transfer among blockage ratio, dimensionless distance from obstruction end and Reynolds number.

Eter et al.(2017) performed experimental investigation in tubes with flow obstructions for heat transfer of CO_2 flows at supercritical condition. They observed that the largest improved effectiveness of the obstructions can be seen at the larger enthalpies in liquid like region.

Zhao and Jiang (2011) conducted an experimental analysis for pressure drop and heat transfer coefficient of supercritical fluid (R134a) in a horizontal tube.

Nomenclature

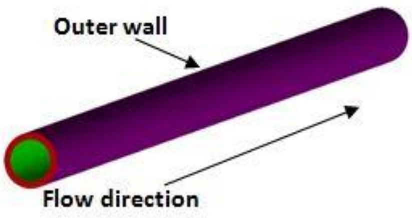
A	Area of flow (m^2)	X	Distance to spacer end in annular channel
C_p	Specific heat (J/kg K)	ρ	Density (kg/m^3)
CHT	Coefficient of heat transfer (W/m^2K)	μ	Viscosity (pa-s)
CHT*	Coefficient of heat transfer without spacer	Re	Reynolds number
D	Hydraulic diameter (m)	X/D	Non-dimensional distance to the spacer end
h	Enthalpy (kJ/kg)	Y^+	Non-dimensional distance normal to the wall
ID	Inner diameter of annular channel (m)	Nu	Nusselt number
K	Thermal conductivity (W/m K)	CFD	Computational fluid dynamics
M	Mass flow rate (kg/s)	Ɛ	Blockage ratio
OD	Outer diameter of annular channel (m)	Nu*	Nusselt number without spacer
P	Pressure (Pa)	q	Heat flux (kW/m^2)
T_w	Wall temperature (^{0}c)		

III. NUMERICAL APPROACH

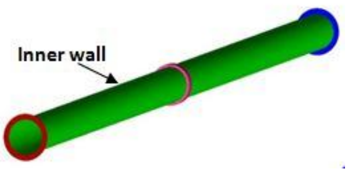
3.1 Fluid flow domain and boundary conditions

The present CFD investigation is focused on effects of spacer on flow and heat transfer behaviour of fluid R-134a at supercritical pressure. The fluid flow domain i.e. annular channel (with spacer) with mesh of present study is shown in figure 1. The hydraulic diameter of annular channel is 6 mm. Two spacers of blockage ratios 0.3 and 0.38 have been used in present investigation. The location of spacer end from inlet is more than 75D to refrain entry effect. In present study, the direction of fluid flow with positive Y direction of coordinate system is vertically upward.

The mass flow rate is set at inlet region for the analysis. Also temperature, turbulence intensity and hydraulic diameter are specified at inlet. The outlet region is selected as the pressure outlet with specified constant pressure. The surface of fuel rod (inner wall) of annular channel is given as constant heat flux, no-slip, smooth wall and outer wall is set as adiabatic wall. The properties of fluid used (R-134a) in present study are considered at supercritical pressure of 4.5MPa and 90^0C. The mass flow rate given at inlet is 0.41469 kg/s. The dimensions of fluid flow domain and boundary conditions are given in table1.



(a)



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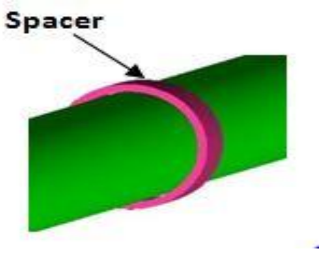

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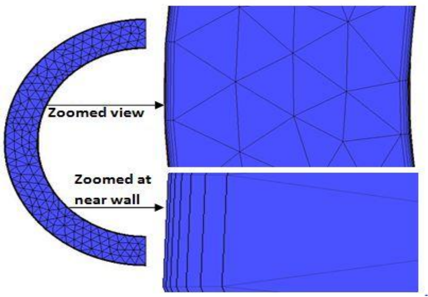


(d)

Figure1: Annular channel with spacer and mesh

Table1: Dimensions of fluid flow domain and boundary conditions

Parameters	**Value**	**Parameters**	**Value**
Length of annular channel	1000mm	Spacer end location	500mm
Length of the spacers	10mm	Inlet	Mass flow rate
Blockage ratio (B.R.) of spacers	0.3& 0.38	Inner wall	Constantheat flux
Inside diameter of annular channel	19mm	Outlet	Pressure outlet
Outside diameter of annular channel	25mm	Outer wall	adiabatic wall

3.2 Turbulence model

The turbulence model used in the present investigation is SST k-ω. The SST k-ω and realizable k-ε turbulence models have been tested for the annular channel without spacer and it is observed that SST k-ω shows more closure result with the experiment data than realizable k-ε turbulence model as shown in figure 2.In the literature for heat transfer of supercritical flows, numbers of turbulence models have been tested and analysed that SST k-ω is more accurate turbulent model for supercritical flows than other turbulent model (Palkoand Anglart, 2008;Jarominand Anglart,2013).

3.3 Grid independency test

In present study, three mesh systems have been used which is given in table 2.For each mesh system, near wall y^+ and cell number are given in the table. Based on comparison of tangential velocity from inner wall to outer wall at distance 400mm from inlet in annular channel, which is shown in figure 3, the case 2 from given table2 of mesh systems is considered as a baseline mesh system for the simulations in the present study.

Table2: Mesh systems for grid independency test

Case	**Number of**	**Minimum y^+ near**
1	1912354	0.3
2	1629725	0.6
3	1306132	0.8

IV. RESULTS AND DISCUSSIONS

In an annular channel with blockage ratio 0.38, the effects of ring type spacer on the wall temperature distribution and heat transfer characteristics are shown in figure 4.The heat flux, mass flow rate and system pressure are taken for analysisas100 kW/m^2, 0.41469 kg/s and 4.5MPa respectively. X/D is dimensionless distance to the spacer end represents the abscissa. The wall temperature distribution and coefficient of heat transfer with blockage ratio 0.38 and without blockage are shown in figure 4 (a) and (b) respectively. Figure 4 (a) shows that, the wall temperature, within the spacer zone is reduced around 9^0C and corresponding coefficient of heat transfer significantly increased, which can be seen in figure 4 (b). Increase of coefficient of heat transfer, within spacer zone is because of the increase in flow velocity due to the presence of the spacer which works as flow blockage cause the reduction in flow area.

Figure 5 shows result between dimensionless distance in abscissa and ratio of coefficient of heat transfer with and without spacer (CHT/CHT*) in ordinate. It can be seen from figure 5 that the effect of spacer is from X/D = 0 to X/D = 30 after this in downstream, the spacer effects are negligible and the flow again becomes to fully developed. The value of CHT/CHT* is found maximum (about 1.8) at location of spacer, which is due to reduced flow area at spacer location.

Figure 6 represents the comparison between CFD result for the ratio of coefficient of heat transfer (CHT/CHT*) for blockage ratio 0.3 and experimental data by Koram and Sparrow (1978) along with correlations given by several researchers for spacer effects at supercritical pressure. The results of the ratio of coefficient of heat transfer (CHT/CHT*) is found in good agreement with the experimental data.The Correlations proposed by several researchers which have been used for comparison (shown in figure 6) and these Correlations are:

By Yao et al., (1982) - working fluid used is single phase water

$$\frac{Nu}{Nu^*} = 1 + 5.55\varepsilon^2 e^{-0.13X/D_h} \qquad (1)$$

By Holloway et al., (2004) - working fluid is single phase water

$$\frac{Nu}{Nu^*} = 1 + 6.5\varepsilon^2 e^{-0.8X/D_h} \qquad (2)$$

By Miller et al.,(2013) - fluid used is single phase steam

$$\frac{Nu}{Nu^*} = 1 + 465.4Re^{-0.5}\varepsilon^2 e^{-7.31\times10^{-6}Re^{1.15}X/D_h} \qquad (3)$$

By Tanase and Groeneveld,(2015) - working fluid used is single phase R-134a

$$\frac{Nu}{Nu^*} = 1 + 3.58 \times 10^{-5} Re\varepsilon^{\{0.47\ln(Re)-3.32\}} e^{-0.13X/D_h} \qquad (4)$$

Where, D_h is hydraulic diameter.

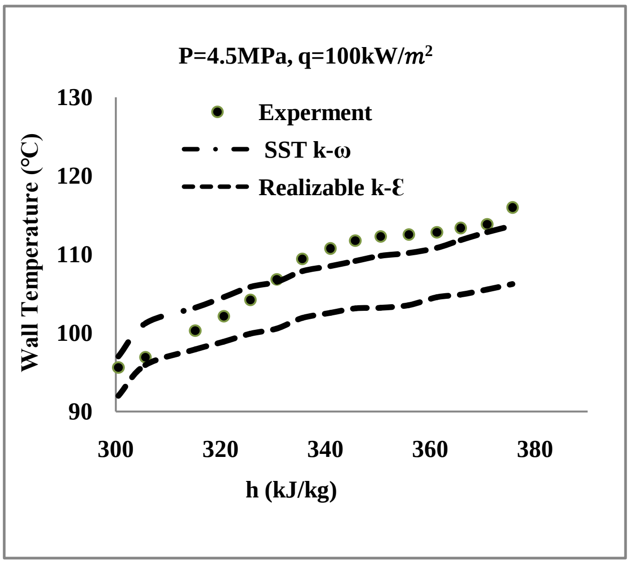


Figure 2: Turbulence model- comparison of CFD result with experiment data

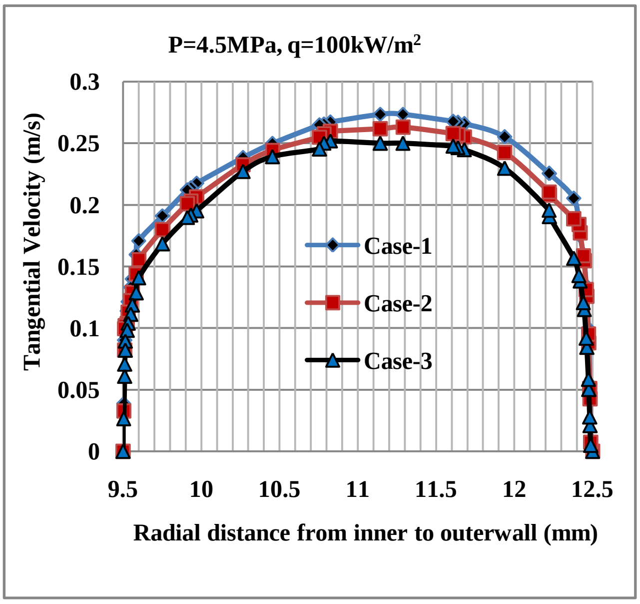
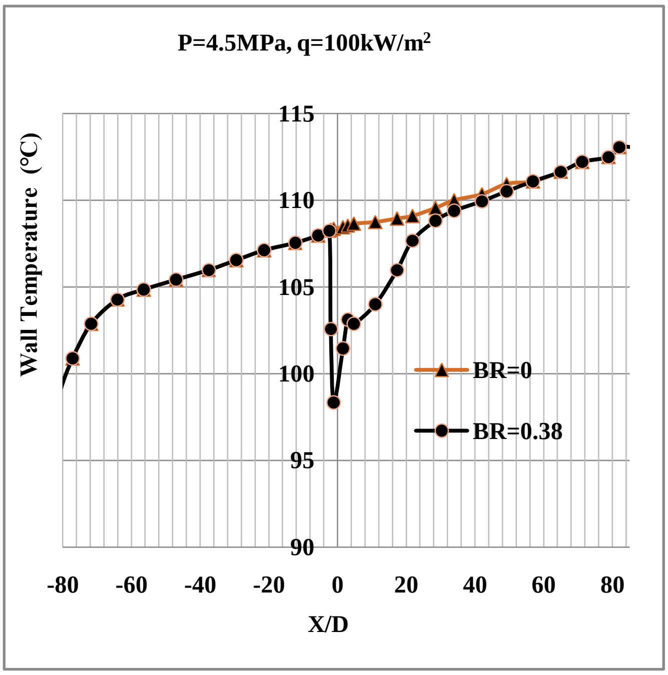


Figure 3: Grid independency test

The spacer effects of blockage ratio 0.38 on flow characteristics are illustrated infigures 7 and 8. Figure 7 shows result between the axial velocity distribution taken in ordinate and dimensionless distance in abscissa. The axial velocity distribution along the annular channel has been taken at distance 11.5 mm and 12 mm from inner wall. It can be seen from figure 7 that at the spacer end, the velocity is significantly increased due to flow area reduction and in downstream to the spacer it come back to fully developed flow. It can also be seen that the axial velocity magnitude for 11.5 mm distance from inner wall is greater than that to 12 mm distance from inner wall except at spacer end and at spacer end it is observed that axial velocity magnitude is greater for 12 mm distance from the inner wall.



(a) Wall Temperature

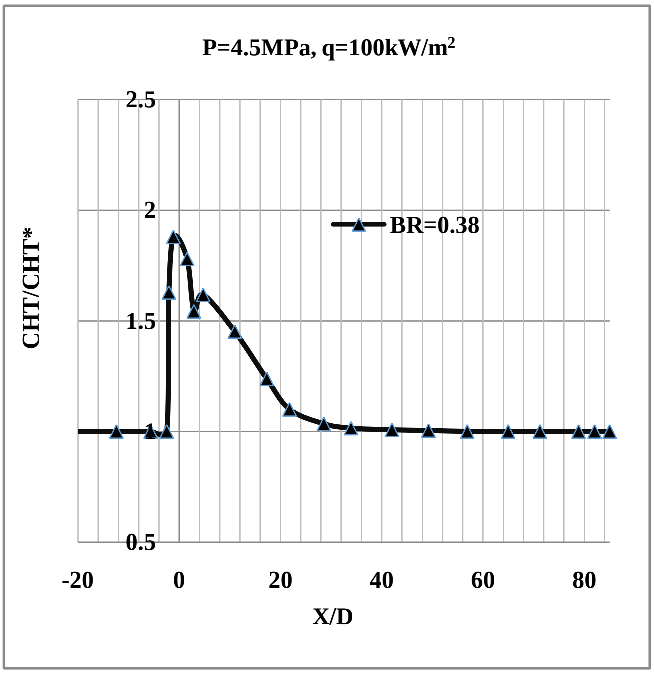
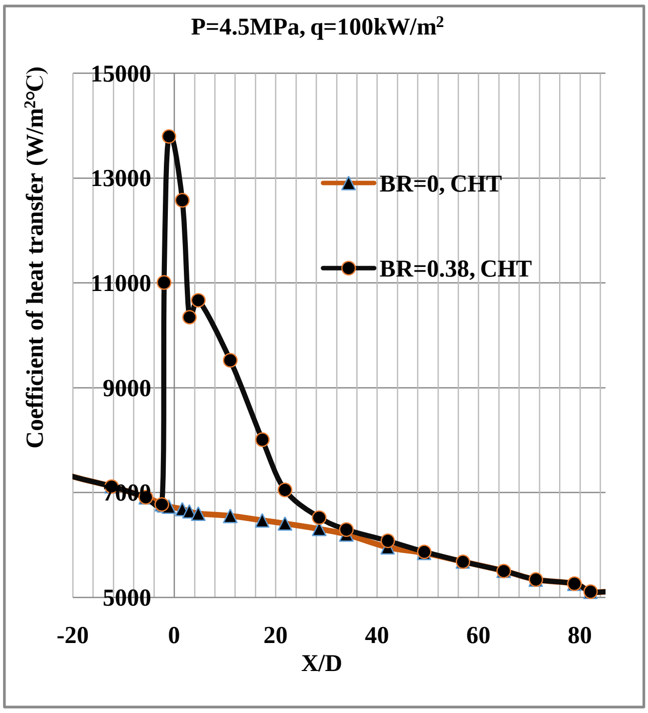


Figure 5: Ratio of coefficient of heat transfer



(b) Coefficient of heat transfer

Figure 4: Spacer effects on heat transfer

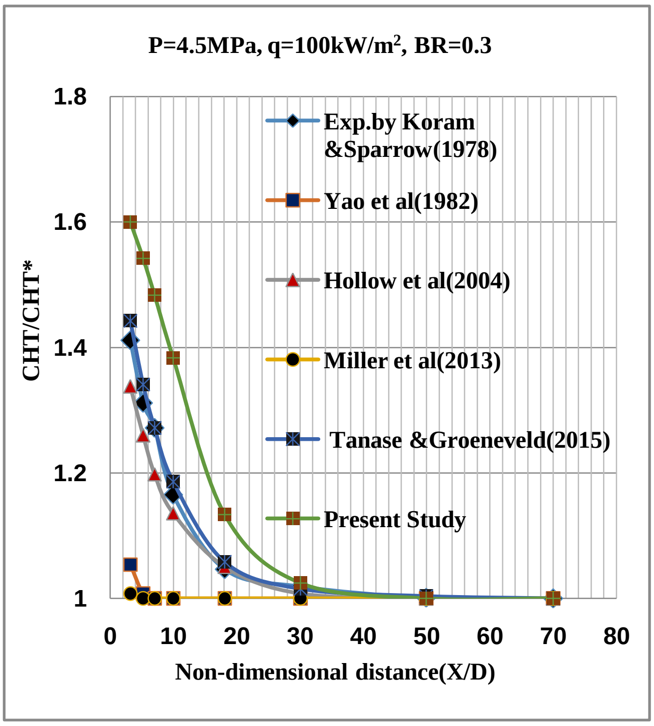


Figure 6: Comparison of experimental data with CFD result

Figure 8 illustrates the result between static pressure and dimensionless distance X/D. The static pressure has been analysed at 11.5 mm and 12 mm distance from inner wall like axial velocity distribution has been observed. Decrease of static pressure at spacer end is significant because of reduction in flow area due to spacer. Decreased static pressure results in reduced pumping power consumption of fluid. Also before and after the spacer, there is slightly decrement of static pressure.

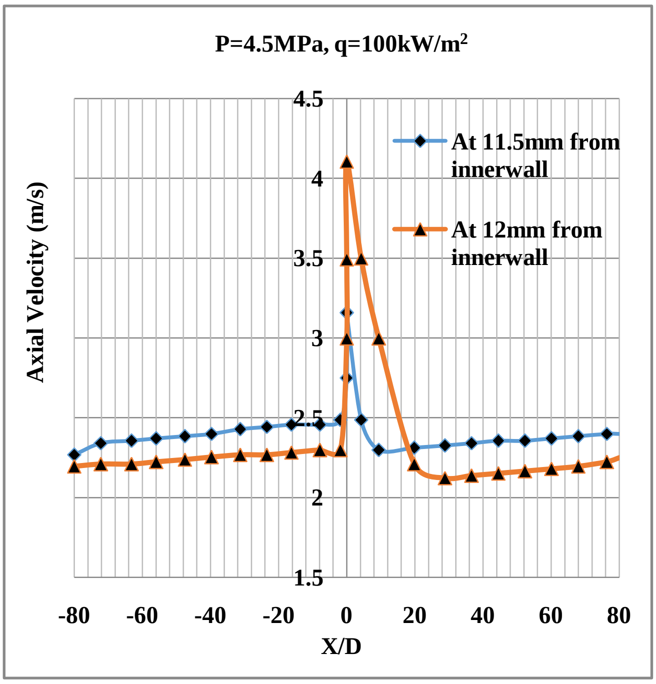


Figure 7: Axial velocity profile

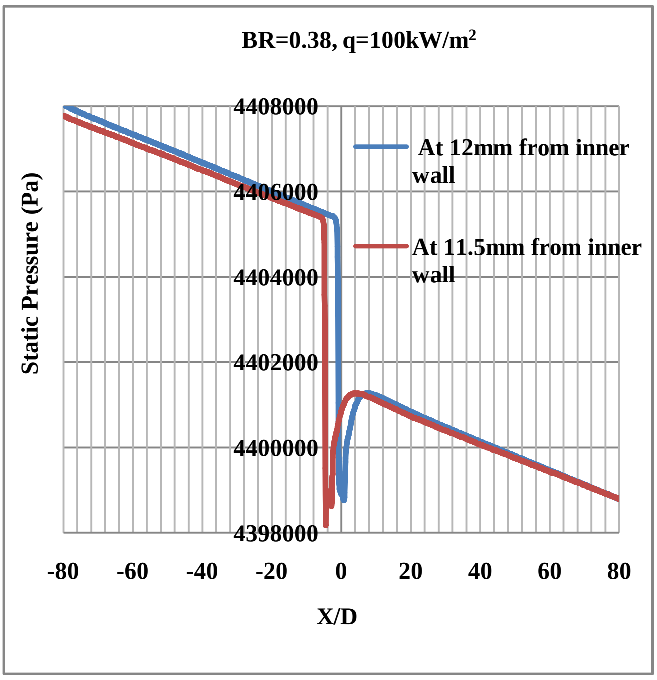


Figure 8: Static pressure distribution

V. CONCLUSION

In an annular channel, a numerical analysis has been carried out to predict the effects of ring type spacer on characteristics of heat transfer and flow behaviour of R-134a flows at supercritical pressure. CFD code (ANSYS Fluent) has been used for simulation. Turbulent model used in present study is SST k-ω. Detailed analysis has been carried out for the spacer effects on flow characteristics and heat transfer. The following conclusions have been drawn:

- The wall temperature, within the spacer zone is reduced around 9^0C and corresponding coefficient of heat transfer significantly increased.
- Ratio of coefficient of heat transfer with and without spacer (CHT/CHT*) is found ingood agreement with the experimental result.
- At the spacer end decrease of static pressure and the increase of velocity are significant due to flow area reduction and in downstream to the spacer,flow again become to fully develop.
- Decreased static pressure results in reduced pumping power consumption of fluid.

Conflict of Interest

The authors confirm that there is no conflict of interest for this publication.

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