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Determination of Heat Transfer Rate and Temperature Dependent Thermophysical Properties of Supercritical Carbon Dioxide (SCCO$_2$) to be Used in Cryocoolers Of Cryogenic Refrigeration System

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Abstract

In present scenario, the use of Supercritical fluids are increased enormously due to their desired thermophysical properties such as higher density with lower viscosity. The need of Supercritical Carbon dioxide (SCCO$_2$) in cryocoolers to be used in Natural Circulation cryogenic refrigeration system is still need to be studied to determine the heat transfer rate for designing better cryocooler. The heat transfer rate depends on thermophysical properties of SCCO$_2$. Hence, it is necessary to predict the temperature dependent thermophysical properties of SCCO$_2$ such as Thermal conductivity, viscosity, density and specific heat. In this context, study is carried out with a wide temperature ranges from 305K to 350K and pressure ranges from 75 bar to 100 bar with a raise in 5K temperature and 5 bar pressure. The heat transfer rate is predicted by analyzing the natural circulation loop modeled and analyzed in commercial software above to critical operating pressure and temperature of SCCO$_2$. Boundary conditions are imposed on the model to compatible with the real time application. From the investigation it is concluded that SCCO$_2$ is having better properties than carbon dioxide and the heat transfer rate is also enhanced. Hence, the use of SCCO$_2$in cryocooler of cryogenic refrigeration system is better compared to CO$_2$.

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Keywords:

Supercritical Temperature;
Supercritical Pressure;
Temperature dependent thermophysical properties;
Supercritical Carbondioxide (SCCO$_2$);
Natural Circulation Loop;
Heat transfer rate

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1. Introduction

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Carbon dioxide being an colorless and odorless gas is present in the atmosphere. Composing of double carbon atom, while bonded to two oxygen atoms. The trace of carbon dioxide in atmosphere is 0.04 present, primarily exists in the form of gas. Figure 1 shows the critical temperature and pressure of carbon dioxide. In natural circulation flow is driven by pressure gradient generated due to variation in density. The principal of natural circulation is employed in applications like boilers, thermal, solar, refrigeration and waste heat recovery. Due to the absence of mechanical actuating components, natural circulations has certain advantages over circulation. Due to the addition of inert gas to supercritical solvent, it will become poor solvent, due to expansion. The utilization of supercritical carbon dioxide is the major thrust area of research, as a working fluid, in this decade. Due to the inflammability and eco-friendly response of Supercritical Carbon dioxide, is the primary reason for the selection of Supercritical Carbon dioxide. The thermal characteristics of SCCO2 aids in predicting the heat transfer behaviour. Utilizing SCCO2 (working fluid), results in less deterioration of ozone layer. In 1965, Karl K Knap [1] et al studied the free convection heat transfer of carbon dioxide near critical point. Igor Pioro [2] laid the discussion about the thermophysical properties of water at supercritical conditions. For the processing of supercritical fluid in agricultural product has focused on extraction mode by using super critical carbon dioxide was studied by Jerry W king et al [3]. Nediljko Budisa et al [4] laid the use of SCCO2 in biotechnology for the stability of enzymes. The phase behavior, pressure and the fluid property linked with SCCO2 injection to improved hydrocarbon recovery (IHR) as studied by Abdullah Al Abri [5] et al. The behavior of corrosion of carbon steel in super critical carbon dioxide-water was studied by the Yoon Seok Choi [6] et al. The fluid dyeing method using supercritical carbon dioxide is studied detailed by Zheng Laijiu [7] et al. The heat transport fluid in earth loop can be enhanced using supercritical carbon dioxide and also as the surface plant working which is mentioned by the Donald W Brown [8] et al. Supercritical carbon dioxide behaviour in the heat exchange performance is studied detailed by Yan Chen [9] et al. Flow and heat transfer behavior of supercritical CO2 in natural circulation loop system is studied by Xin Rang Zhang et al [10]. Ajay Kumar Yadav et al [11] analyzed circulation loop type using carbon dioxide and other fluids for various refrigeration. Ummid I Shaikh et al [12] made a conclusion that in circulation loop of fluid will increase with hot fluid flow rate. Padalkar A S et al [13] concluded CO2 as the best natural refrigerant. Experiments were performed for studying thermohydraulic performance by Nikitin et al [14]. Heat transfer rate from loop and thermal conductance have strong conjunction of the pressure of CO_2.[15]. The thermo physical property of carbon dioxide is shown in table 1 for supercritical temperature and pressure which is calculated by using NIST data.

Table 1 Thermophysical properties of carbon dioxide at super critical temperature and pressure

Thermophysical property of carbon dioxide at super critical temperature (304.2k) and pressure (73.9 bar)			
Density (kg/m3)	Thermal conductivity (W/mK)	Specific heat (kJ/kgK)	Viscosity (kg/ms)
0.00034646	0.072962	32.152	0.000026569

In the present work, natural circulation for thermophysical of supercritical nitrogen is studied. The critical operating conditions of super critical carbon dioxide is found to be 304.2K and 73.9 bar respectively. Moreover the thermophysical properties over wide operating range is also studied.

2. Research Methodology

The estimation of thermophysical properties for supercritical carbon dioxide at temperature and pressure of 304.2K and 73.9 bar is calculated with various pressures and a range of temperature. The temperature is taken from 300K to 350K which is just above the critical temperature of CO2 and the pressure chosen are 75 bar to 100 bar with a increment of 5 bar. The estimated properties are density, viscosity, thermal conductivity and specific heat. The commercial ANSYS software compatible with Computational Fluid Dynamics (CFD) is used to determine the Heat Transfer Coefficient at hot and cold sides. Figure 2 shows the geometry of NCL considered for analysis, the fluid in the loop is heated by heat which is extract from the fluid in the hot heat exchanger and is cooled by the fluid in the cold heat exchanger. The fluid is circulated by the buoyancy effect due to density difference as a result of cooling and heating. The assumptions considered for analysis are such as fluids are under steady state, pipes are perfectly insulated and internal fluid ($SCCO_2$) and external fluid (Water) are in the single phase.

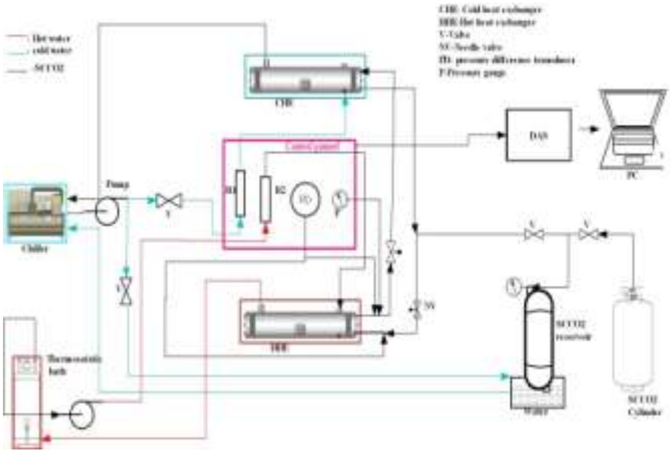

Figure 1 Natural circulation loop of supercritical carbon dioxide

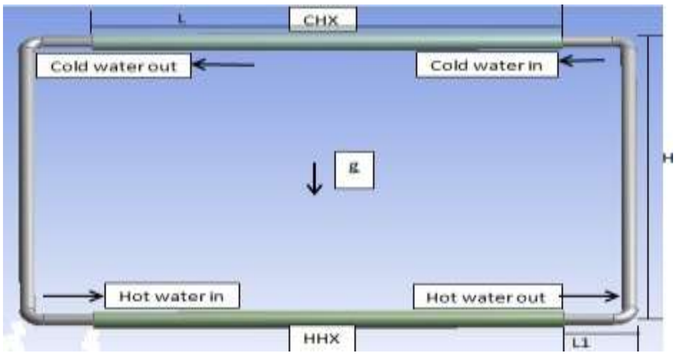

Figure 2 Geometry of Natural circulation loop

Figure 3 shows the meshed geometry of NCL with sizing of element is given as 3mm the geometry having 212570 nodes and 948699 elements in this geometry and skewness is 7.29 which is less than 10. The meshing is generated to the named bodies. The cell zone condition is used to define the porous zone, energy sources in the fluid or solid zones and the various operating conditions like temperature and pressure The boundary conditions are imposed on the NCL are mass flow rate which is given as 0.3m/s and the temperature of cold water and temperature of hot water which is 283K and 353K respectively. The energy and momentum terms are iterated with the second order upwind. The PRESTO (Pressure staggering option) scheme is used in order to discretize the pressure term. In the walls no slip boundary conditions are used. Here the RNG (Renormalization Group) and k-ϵ models are used as the turbulence schemes.

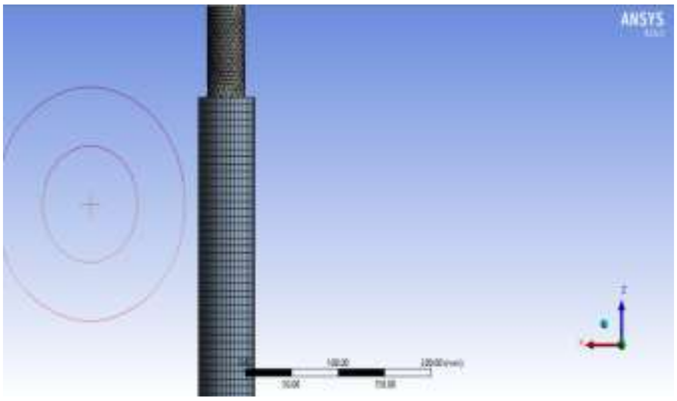

Figure 3 Geometry after meshing

3. Results and Analysis

3.1 Thermophysical properties of SCCO2

The mechanism of natural circulation is driven by pressure gradient. With variation of thermophysical properties with temperature is temperature and pressure.

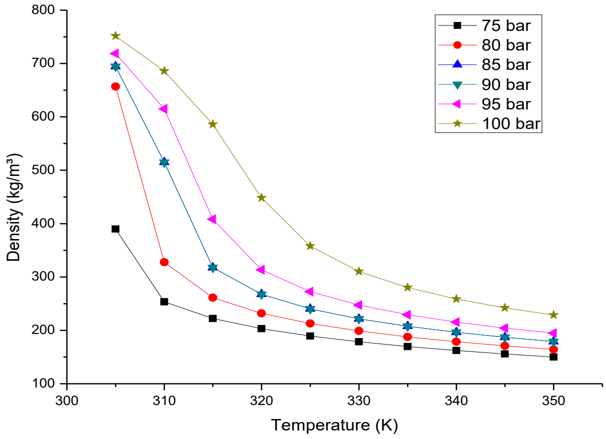

Figure 4 Variation of density as a function of temperature (300K-350K) and pressure (75 bar-100 bar)

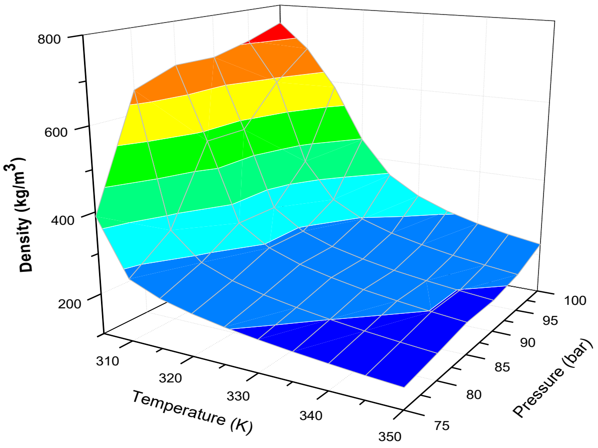

Figure 5 Variation of density as a function of temperature (300K-350K) and pressure (75 bar-100 bar)

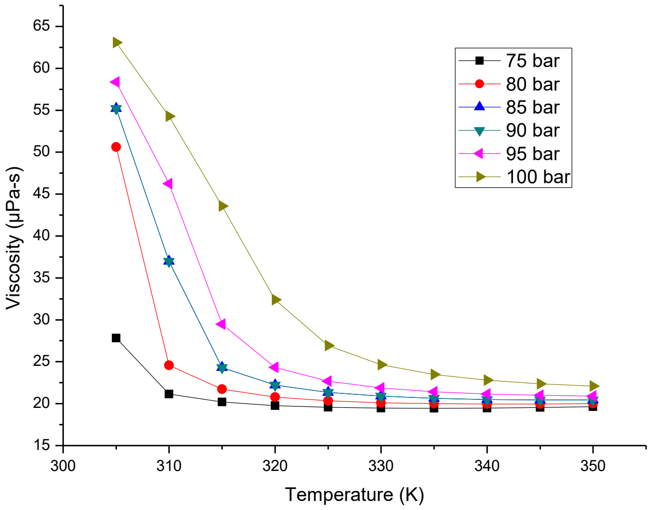

Figure 6 Variation of viscosity as a function of temperature (300K-350K) and pressure 75bar-100 bar)

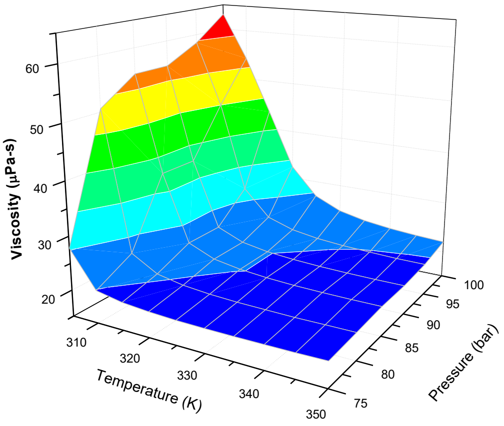

Figure 7 Variation of viscosity as a function of temperature (300K-350K) and pressure 75bar-100 bar) in 3D visual

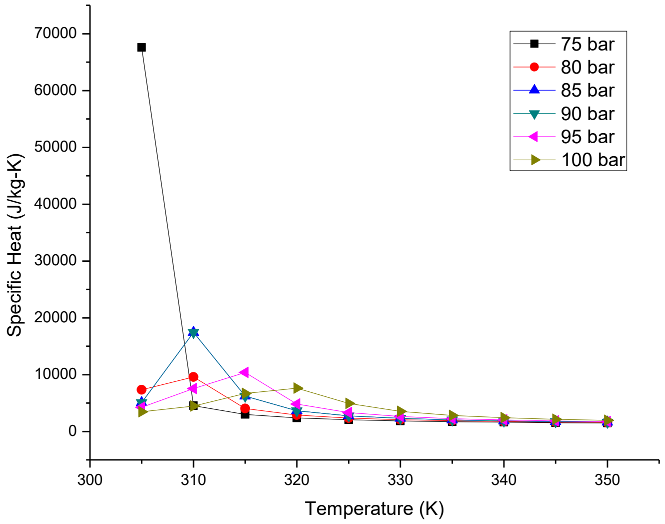

Figure 8 Variation of specific heat as function of temperature (300K-350K) and pressure (75bar-100bar)

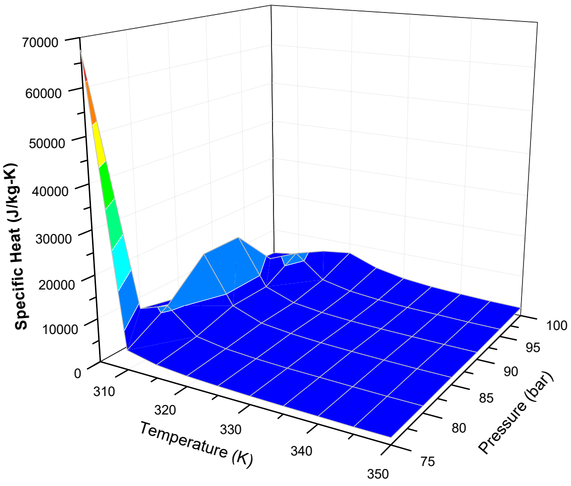

Figure 9 Variation of specific heat as function of temperature (300K-350K) and pressure (75bar-100bar) in 3D visual

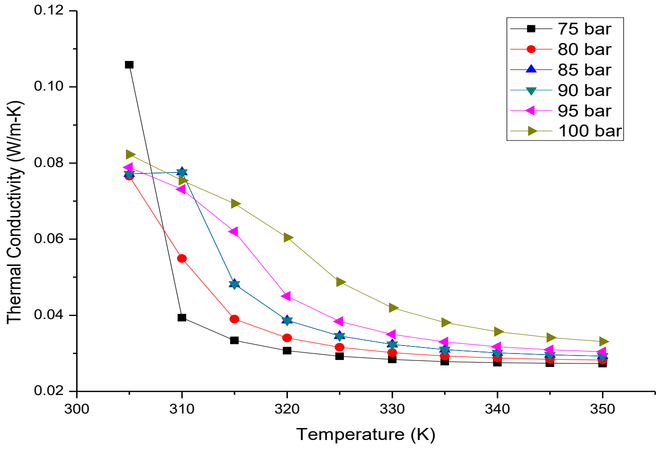

Figure 10 Variation of thermal conductivity as a function of temperature (300K-350K) and pressure (75bar-100bar)

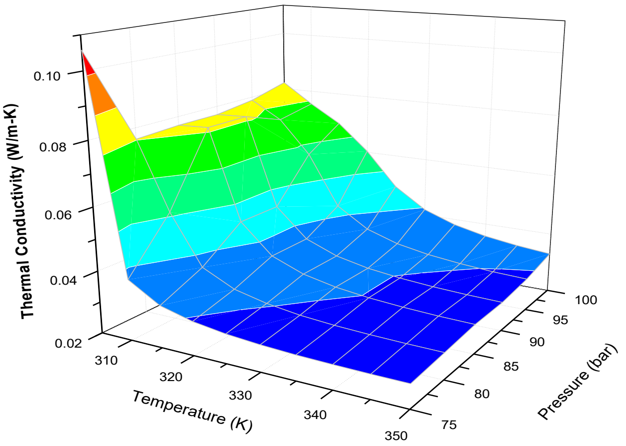

Figure 11 Variation of thermal conductivity as a function of temperature (300K-350K) and pressure (75bar-100bar) in 3D visual

Figure 4and Figure 5 shows the effect of temperature on density at pressure it is observed that density is decreasing experimentally with increase in the temperature (300K-350K). The pressure is increasing from 75 bar to 100 bar the density is showing to increase. The diverging coefficient of expansion is the reason to cause huge variation in density for small change in temperature. Figure 6 and Figure 7 shows the viscosity is decreasing experimentally with increase in the temperature. However, pressure is increasing the viscosity is slightly increasing. Moreover, Figure 8 and Figure 9 shows the specific heat, increase in the temperature as well as it is showing increase with increase in the pressure from 75bar to 100 bar. Figure 10 and Figure 11 shows the thermal conductivity is decreasing with increase in the temperature (300K-350K) and is increasing with increase in the pressure (75bar-100bar). Also it is observed that the density, viscosity, and thermal conductivity is increasing with increase in the pressure (75bar-100bar). It is due do to movement of molecules. As the pressure increases the molecules are moving closer. And there is observed that there is change in the thermophysical property for 5K rise in the temperature near critical pressure and temperature.

3.2 Determination of heat transfer coefficient

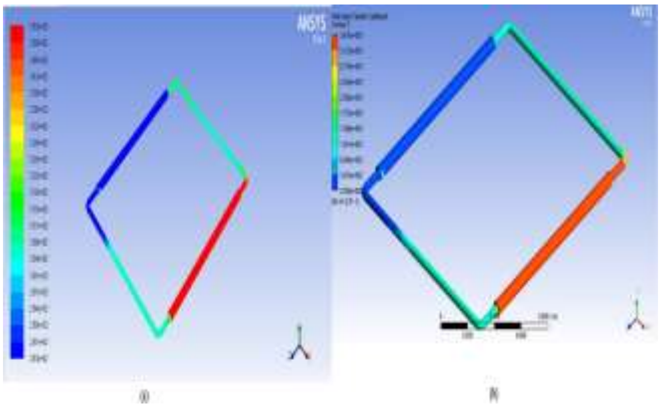

Figure 12 (a) Temperature distribution (b) Heat flux at 75 bar and 305K for NCR

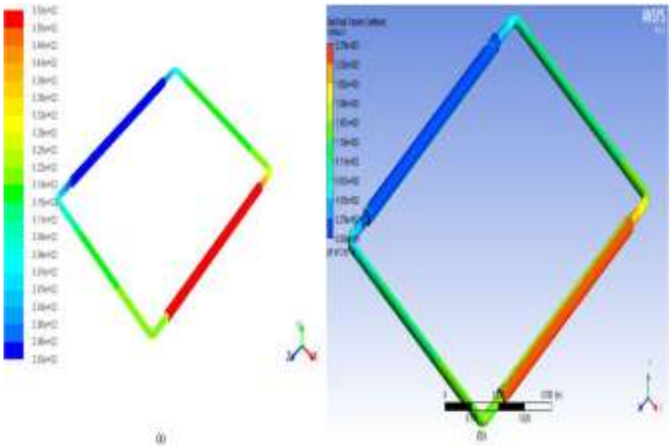

Figure 13 (a) Temperature distribution (b) Heat flux at 80 bar and 305K for NCR

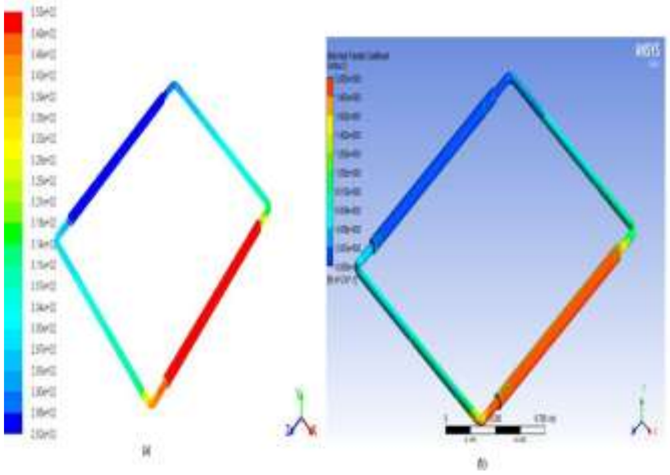

Figure 15 (a) Temperature distribution (b) Heat flux at 85 bar and 305K for NCR

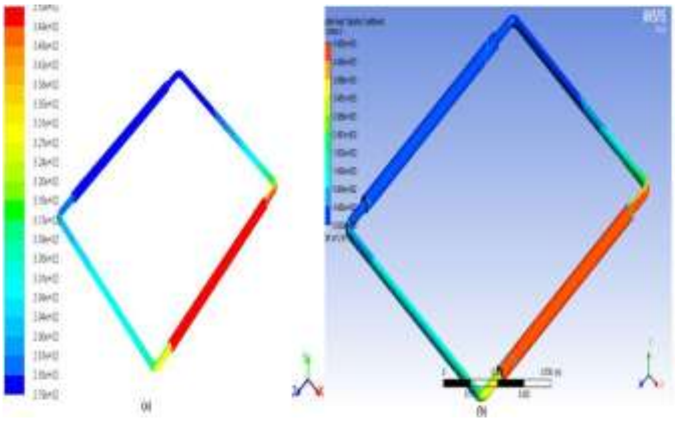

Figure 14 (a) Temperature distribution (b) Heat flux at 90 bar and 305K for NCR

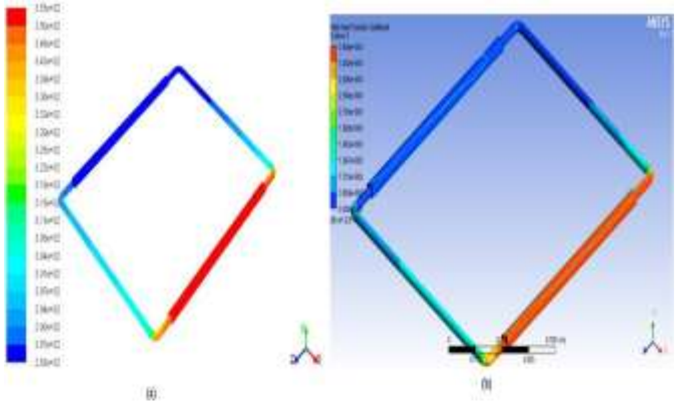

Figure 15 (a) Temperature distribution (b) Heat flux at 95 bar and 305K for NCR

From figure 13 to figure 15 (a) shows the temperature distribution of the natural circulation loop with temperature differences occurred in the all system, (b) shows the heat transfer coefficient is more at the hot heat exchanger and less at the cold heat exchanger.

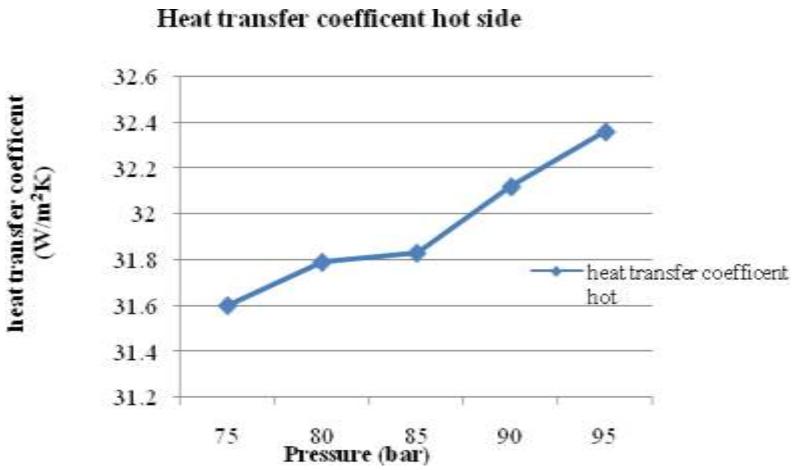

Figure 16 Pressure Vs heat transfer coefficient at hot side

From the graph it is clear that at the supercritical pressure(75bar) the heat transfer is low and as per the pressure increases the heat transfer rate is also increasing that means as the pressure increases the heat transfer rate is increasing while the heat transfer rate of carbondioxide is more that the supercritical carbondioxide. Heat transfer coefficient is higher at higher pressures. The enhancement of heat transfer is higher if the heat transfer coefficient is higher. However, it is very difficult to operate at higher pressures.

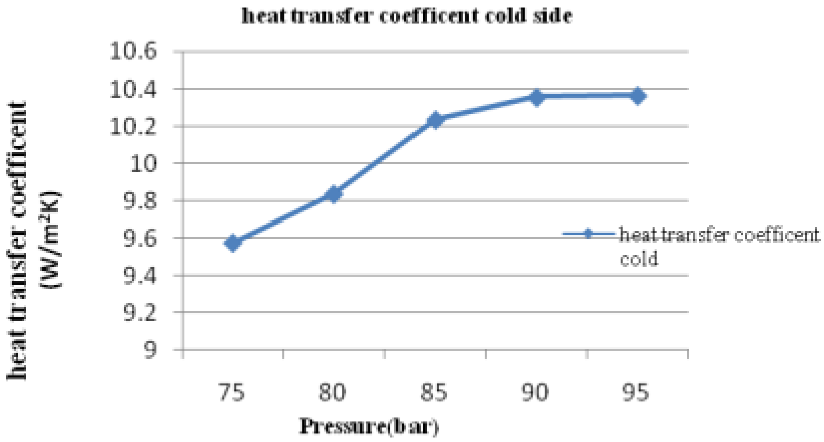

Figure 17 Pressure Vs heat transfer coefficient at cold side

From the above graph it is clear that the minimum heat transfer is obtained at the supercritical pressure and temperature at the both hot and cold side. Hence the pressure increases the heat transfer rate is also increasing in both side. Density factor is considered as the driving force for natural circulation loop. Heat transfer coefficient is higher at higher pressures . The enhancement of heat transfer is higher if the heat transfer coefficient is higher. However, it is very difficult to operate at higher pressures

4. Conclusion

The thermopyhsical properties such as density, viscosity, thermal conductivity and specific heat of Supercritical carbon dioxide for natural circulation loop in Cryogenic refrigeration system. Density and Viscosity of $SCCO_2$ is decreasing with the increase in the temperature and increasing with the increase in the pressure. However, Density and Specific heat is higher at the critical pressure and temperature. Further increase in the temperature and pressure specific heat is decreasing gradually. The model of natural circulation loop is designed in ansys 14.5. The simulation is carried by applying the boundary conditions on natural circulation loop in Fluent 14.5 From the analysis carried it is observed that the $SSCO_2$ has better thermo physical properties and lower heat transfer rate than Carbon dioxide. The heat transfer coefficient is more at hot heat exchanger and less at cold heat exchanger. When the pressure increases heat transfer rate slightly increases up to 85bar and it increases drastically after 85 bar.

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