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Analytical Investigation of the Discharge Valve Dynamics in a Reciprocating Compressor for Trans-critical CO_2 Refrigeration Cycle

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Abstract

In this project, analytical investigations are made to determine the thermodynamic performance of the compressor. By varying design parameters compressor speed 60m/s, 80m/s, 100m/s and 120m/s, the movement of the discharge valve in the reciprocating CO_2 compressor is measured in order to investigate the major factors that influence the valve dynamics. 3D model of the valve is done in Pro/Engineer and CFD analysis and thermal analysis is done on the discharge valve in Ansys. Thermal analysis is done by varying the materials Stainless Steel, En8 Steel and Cast Iron.

Keywords: *compressor speed, reciprocating* CO_2 *compressor, Discharge Valve, En8 steel, Cast Iron.*

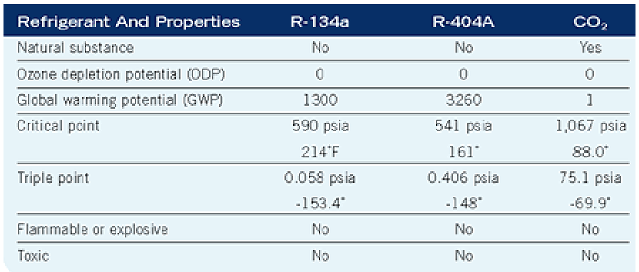
1. Introduction

As an environmentally friendly refrigerant, CO_2 has gained more and more attention. Different institutions and companies have developed CO_2 compressors for different applications. Some small CO_2 compressors have been developed in Japan for the use in domestic heat pump water heater and automobile air-conditioner. These compressors are mostly scroll and rolling piston types, with power around 1-2kW and COP around 4. Large and medium CO_2 compressors have been produced by Dorin and Bock for the use in commercial applications.

Compared with traditional fluorocarbon-based refrigerants, CO_2 has lower critical temperature (31.ć) but higher critical pressure (7.37MPa). Due to the transcritical operation of the cycle, CO_2 compressor is working under much higher pressure, 5-10 times higher than the standard compressor. This high pressure causes large forces, which greatly challenges the design of key components such as crank, connecting rod, bearings and suction/discharge valves.CO_2 has a high volumetric capacity ($22.6 MJ/m^3$ at 0ć), which is 1.58, 5.12 and 8.25 times as much as NH3, R22 and R12 respectively. Thus, the swept volume of CO_2 compressor is smaller than the standard compressor. So, it could be possible to design the compressor compact and cost effective compressor. However, it becomes more difficult to arrange the valves with sufficient flow area in a relatively small space.

The high pressure difference, combined with the large density of CO_2, bring great bending and impact stresses to the valves. Also, the high speed (2900rpm) of CO_2 compressor causes high impact velocities. Researchers have reported that the discharge valve and the spring have relatively short life and are easy to break due to improper material, design and manufacture. Robust design of the valves is crucial to improve the reliability of the CO_2 compressor. Junghyoun Kim (2006) analyzed the valve dynamics of a hermetic reciprocating compressor using R134a as refrigerant. The dynamic behavior of the valves and the pressure-volume diagram were obtained. However, the discharge pressure is much lower than the critical pressure and the property of the two refrigerants was quite different. Jeffrey J.NIETER (2006) analyzed the discharge port and valve and the results revealed excessive over-pressure loss. Detailed experimental research about the valve dynamics for transcritical CO_2 cycles is unavailable now.

Table 1. Properties of CO2 (R-744) compared with those of R-134a and R-404A.



Refrigerant And Properties	R-134a	R-404A	CO_2
Natural substance	No	No	Yes
Ozone depletion potential (ODP)	0	0	0
Global warming potential (GWP)	1300	3260	1
Critical point	590 psia 214°F	541 psia 161°	1,067 psia 88.0°
Triple point	0.058 psia -153.4°	0.406 psia -148°	75.1 psia -69.9°
Flammable or explosive	No	No	No
Toxic	No	No	No

2. CO$_2$ in Transcritical Refrigeration:

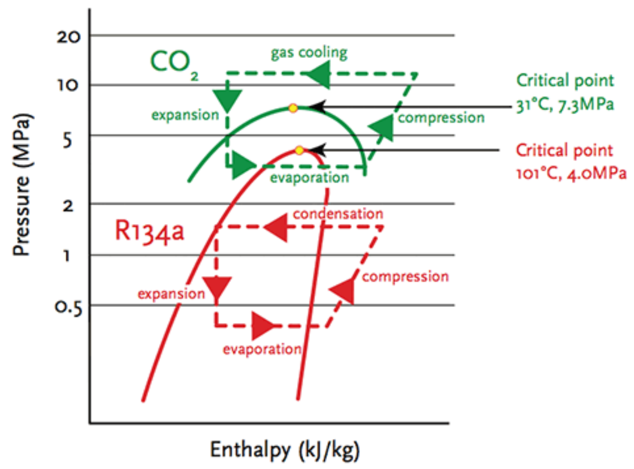


Fig 2.1. Basic comparison of simple refrigeration cycles

In transcritical refrigeration cycles, CO$_2$ operates at much higher pressures than traditional HFC and ammonia systems. Modern manufacturing methods have enabled the production of low-cost components capable of operating at the high pressures required for CO$_2$ refrigeration. This includes small domestic units, heat pumps, supermarket applications, and, to a lesser extent, industrial applications. Smaller CO$_2$ systems tend to use unitary transcritical systems, whereas larger, commercial and industrial systems are more likely to employ CO$_2$ as a low temperature refrigerant in cascade systems, together with other refrigerants such as ammonia being used as the high temperature refrigerant. There have been developments in small scroll compressors and reciprocating compressors specifically for transcritical CO$_2$ systems. CO$_2$ has a higher volumetric refrigeration capacity than traditional refrigerants (so requiring less displacement) but at much higher pressure differentials. The reduced volume flows of the refrigerant provide opportunities for smaller components. CO$_2$ can also be used as a direct refrigerant, where liquid CO$_2$ is simply pumped under pressure to an evaporator supplying the cooling load, with the vaporized CO$_2$ then passed through a low temperature heat exchanger (still at high pressure) and condensed, ready to be recirculated to the load.

2.1 Subcritical and transcritical cycles:

The R134a cycle has the evaporating process starting off bottom left, where the low temperature refrigerant is a mix of vapour and liquid. As the refrigerant gains heat from the surrounding cooling load (or heat source for heat pump), its enthalpy rises with the refrigerant at constant pressure, until it becomes a superheated gas at the intake of the compressor. The compressor increases the pressure, also adding heat to the refrigerant, and consuming power to drive the motor. The hot, high-pressure, superheated gas enters the condenser, where heat is rejected (or, in a heat pump, passed to the heat transfer medium) and the gas reverts back to a liquid. The warm, high-pressure liquid (often subcooled) passes through a pressure-reducing device (an expansion device) at constant enthalpy. The whole cycle is below the critical point, so is known as a 'subcritical' process. The expansion device is designed primarily to ensure that superheated gas enters the compressor by sensing the condition of the low-pressure refrigerant leaving the evaporator to control the flow.

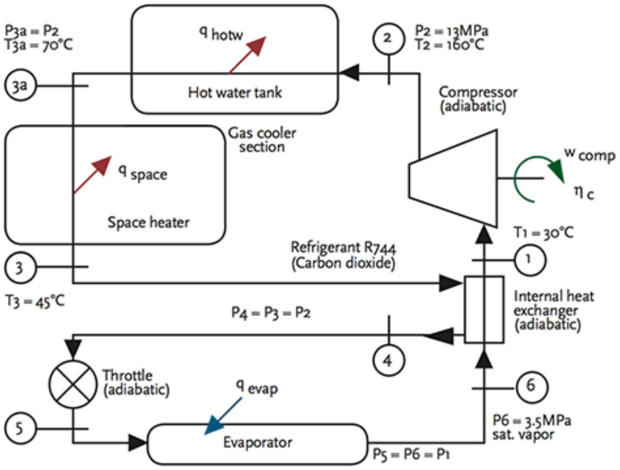


Fig 2.2. CO2 transcritical heat pump operation.

3. Figures, Tables and Equations:

3.1 Figures

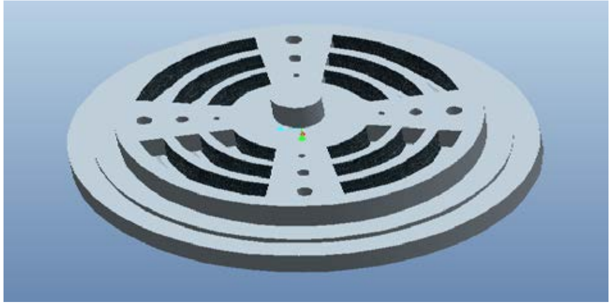


Fig 3.1. 3D Model of Discharge Valve

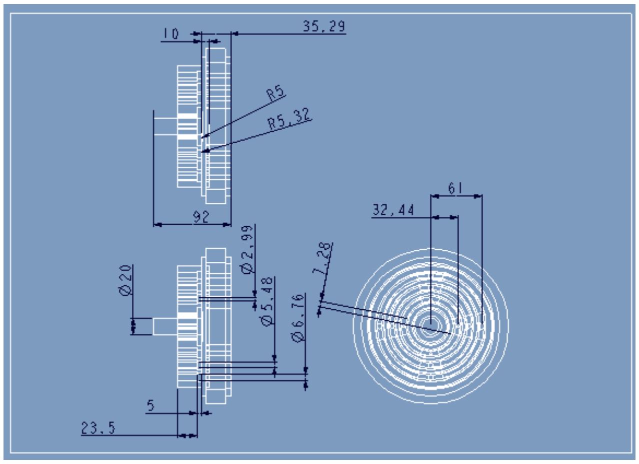


Fig 3.2. 2D Drawing of the Discharge Valve

3.2. CFD analysis by Varying the Compressor Speed

VELOCITY-80 M/S

Fig 3.2.1 Pressure

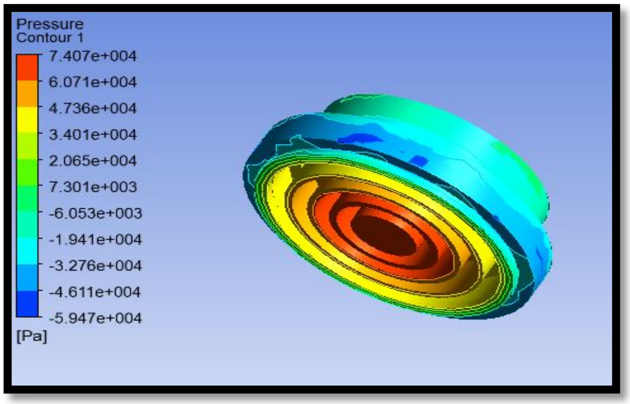


Fig 3.2.2 Velocity

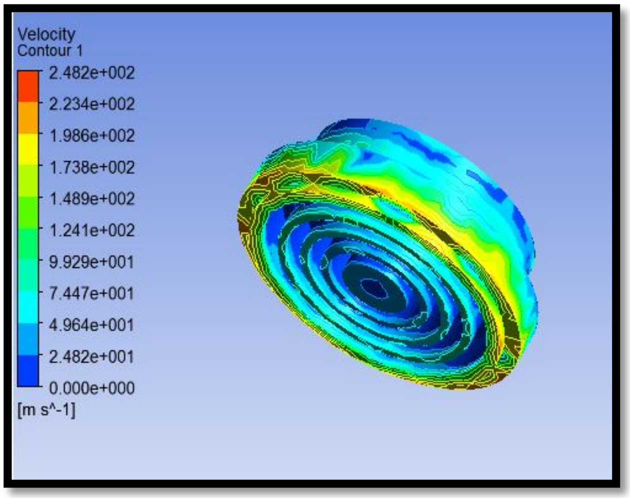


Fig 3.2.3 Temperature

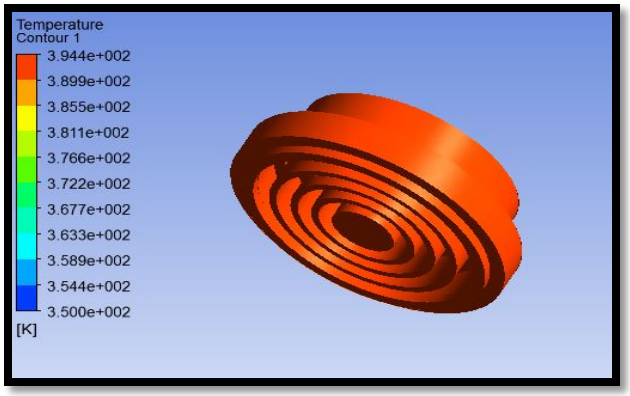
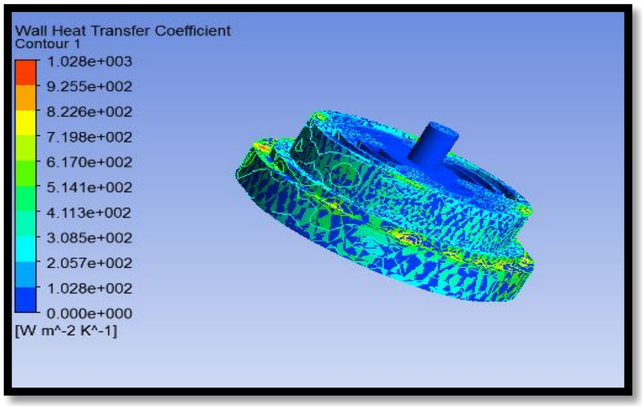


Fig 3.2..4 Heat transfer co-efficient



VELOCITY-100 m/s

Fig 3.2.5 Pressure

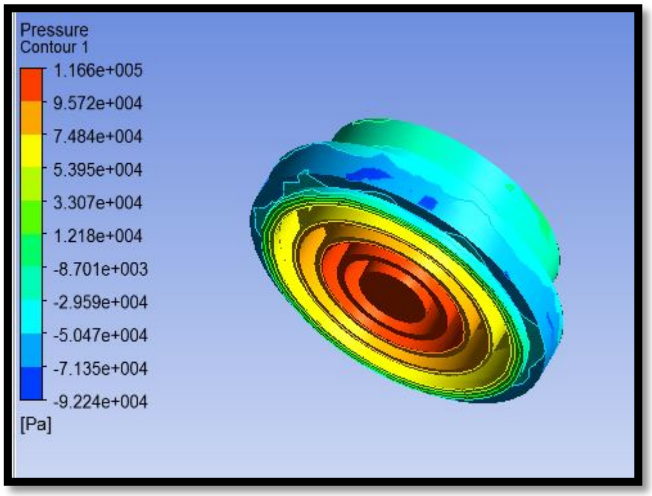


Fig 3.2.6 Velocity

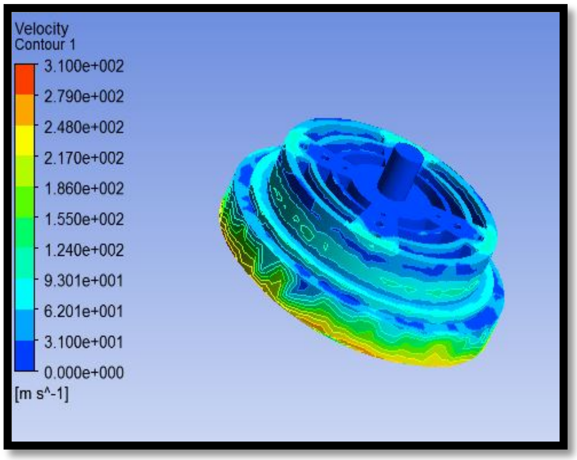


Fig 3.2.7 Temperature

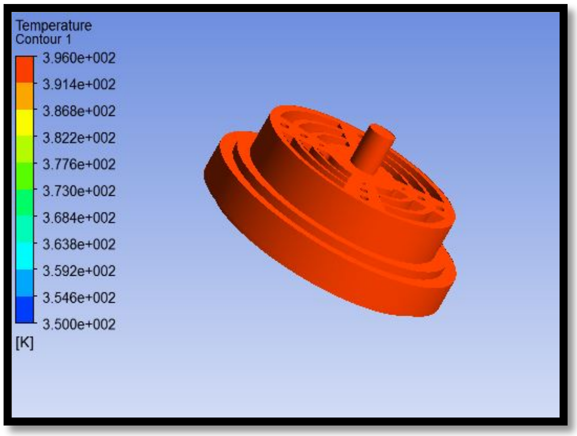
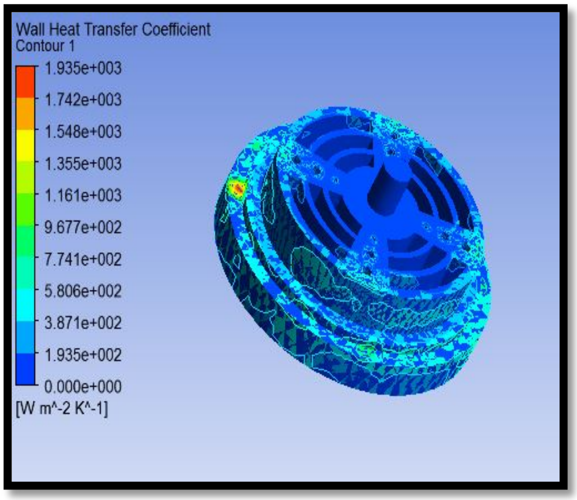


Fig 3.2.8 Heat transfer coefficient



VELOCITY-120 m/s

Fig 3.2.9 Pressure

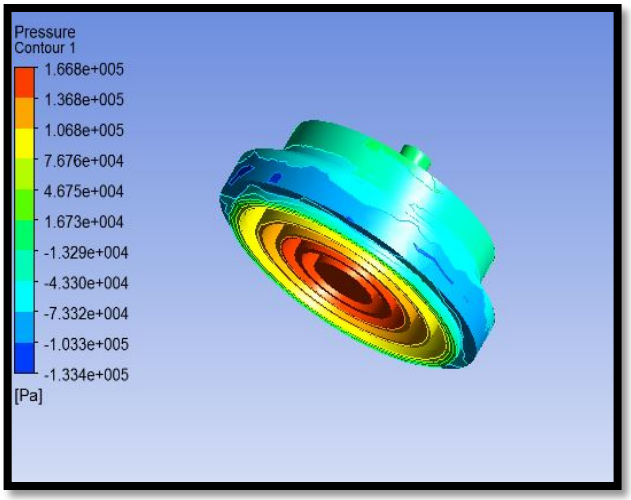


Fig 3.2.10 Velocity

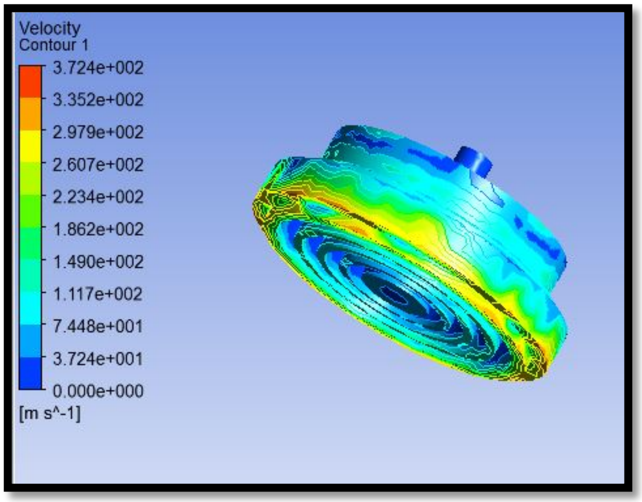


Fig 3.2.11 Temperature

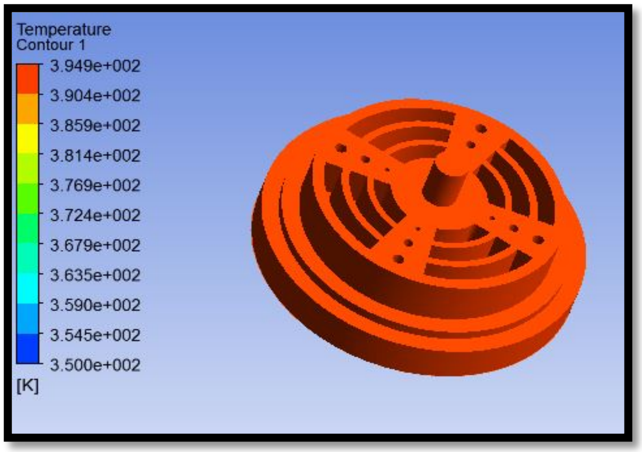
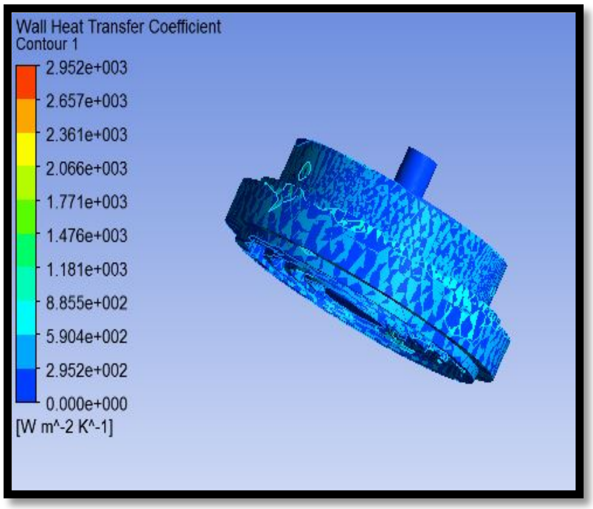


Fig 3.2.12 Heat transfer co-efficient



3.3 Tables

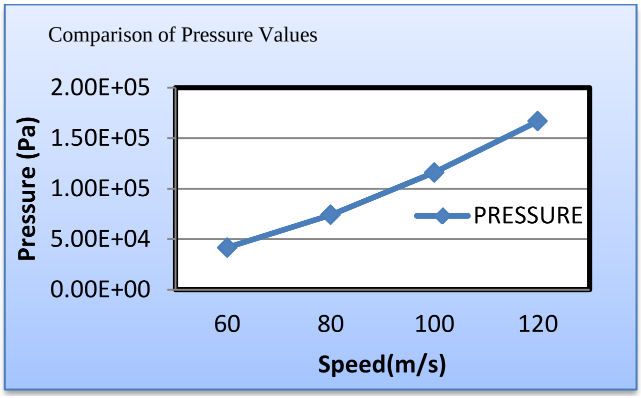
3.3.1 CFD RESULTS TABLE

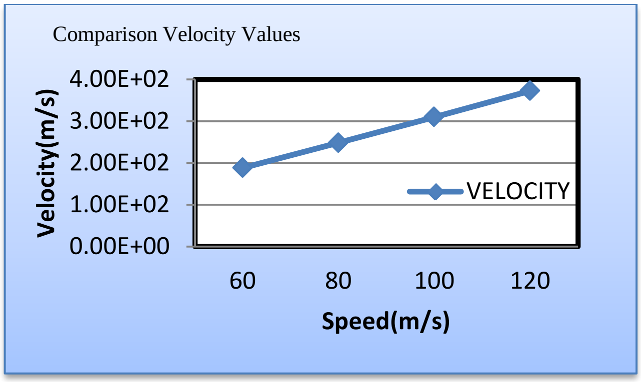
Speed (m/s)	*Pressure (Pa)*	*Velocity (m/s)*	*Temperature (°C)*	*Heat transfer co efficient (W/m^2-k)*	*Mass flow rate (Kg/s)*	*Heat transfer rate (W)*
60	4.157e+004	1.881e+002	3.943e+002	6.971e+002	0.017766	1517.524
80	7.404e+004	2.482e+002	3.944e+002	1.028e+003	0.025038	2138.6226
100	1.160e+005	3.100e+002	3.960e+002	1.935e+003	0.034672	3064.5336
120	1.668e+005	3.724e+002	3.949e+002	2.952e+003	0.04242	3561.9091

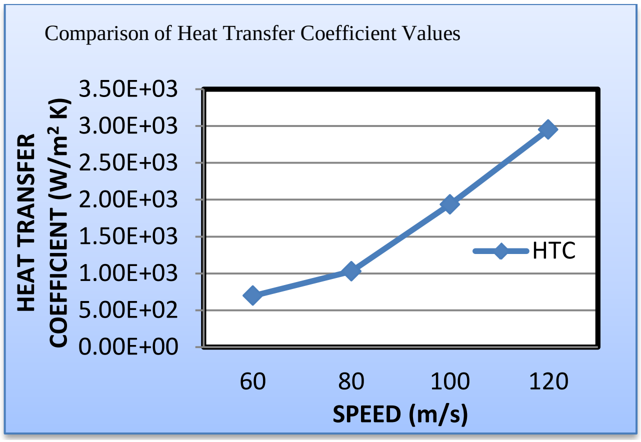
3.3.2 THERMAL ANALYSIS RESULT TABLE

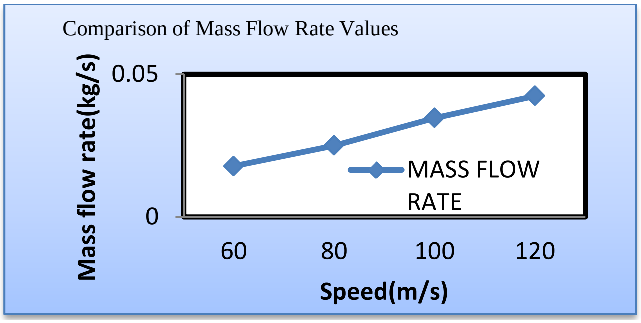
Materials	*Temperature(°C)*		*Heat flux(W/m^2-K)*
	Max.	*Min.*	
Stainless steel	118.09	39.865	0.16399
Cast iron	118.05	50.886	0.37049
EN8 steel	118.04	53.289	0.4031

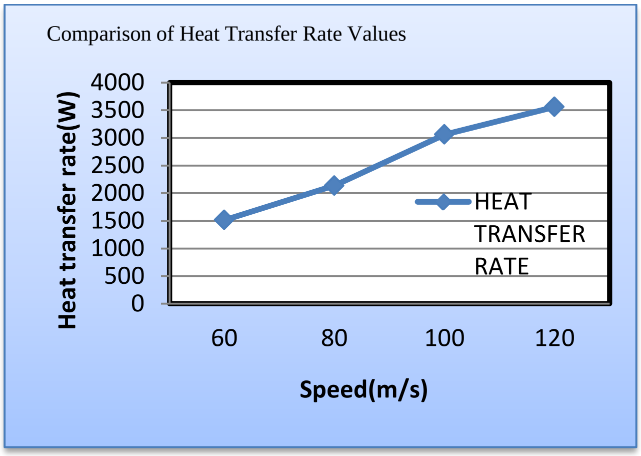
3.4 Graphs











4. Conclusions

I concluded that

1. By comparing the CFD analysis results, the heat transfer rate, heat transfer coefficient, pressure, velocity and mass flow rate are increasing by increasing the compressor speed.
2. By observing the thermal analysis results, EN8 Steel has more heat flux (i.e) heat transfer rate is more.

So it can be concluded that increasing the compressor speed and using EN8 steel is better for better performance.

Acknowledgments

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