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Parametric Study of a Phase Separator used in A/C Automotive System using CFD Tool

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Abstract

The air conditioning system used in automobiles uses oil which lubricates the moving part of the compressor. Excess presence of the lubricant oil in the compressor will cause a hindrance to flow inside the condenser and evaporator which will affect the heat transfer efficiency of the system. The oil is separated at the downstream of the compressor using centrifugal/ impinging on the refrigerant gas flow. The oil exists in the form of droplets in a secondary phase. The main requirement for a good design of the phase separator is to have maximum oil separation with minimum pressure drop of the refrigerant gas. The numerical simulation is carried out using Multiphase Mixture model.

Keywords: Phase separator, multiphase flow, mixture models.

Introduction

Air conditioning compressor is an integral component for an air conditioning system; when it begins reciprocate, lubricant will be very pivotal to protect equipment. But when refrigerant is exhausted from compressor, a little of lubricating oil will be taken away from it and will accumulate inside the compressor eventually. Therefore, an oil-gas separator need be collocated to compressor, which could separate lubricating oil from refrigerant and then lubricating oil would flow back compressor. For the separator construction, the swirling motion is brought about by designing the inlet in such a manner that it forces the gas to enter the unit on a tangent to the inner body wall[1].

There are many different varieties of oil-gas separator available in the market. One such variety is the cyclone phase separator works on the principle of double vortex. The oil-gas mixture is injected into the cylinder using a pipe which is held in tangentially to the separator body is shown in figure 1. As the gas swirls, it moves axially downwards in the outer part of the separation space. In the conical part of the cyclone, the gas is slowly forced into the inner region of the cyclone, where the axial movement is upwardly directed and the downwardly directed axial flow takes oil particles along with it. This flow pattern is often referred to as a 'double vortex': an outer vortex with downwardly directed axial flow and an inner one with upwardly directed flow.

Cyclone phase separator is simple, compact with less weight, and has low capital and operational costs. The Cyclone Phase has a wide variety of potential applications, varying from only partial separation to a complete phase separation[2]. The analysis of fluid flow and particle motion in a cyclone is very complicated. The aerodynamics inside the cyclone create a complex two-phase, three-dimensional, turbulent swirling flow with a confined outer free vortex (irrotational flow) and a low-pressure, highly turbulent inner forced vortex (solid body rotation). The transfer of fluid from the outer vortex to the inner vortex apparently begins below the bottom of the exit tube and continues down into the cone along the natural length of the vortex of a cyclone[3]. The length of the inner vortex core is also referred to as the cyclone effective length, which does not necessarily reach the bottom of the cyclone[3]. Particle/ Fluid collection in the cyclone is due to the induced inertia force resulting in radial migration of particles suspended in the swirling gas to the walls and down the conical section to the dust outlet and the gas exits through the vortex finder. Flow near the cyclone wall is assumed to be laminar, although it is usually somewhat turbulent[4].

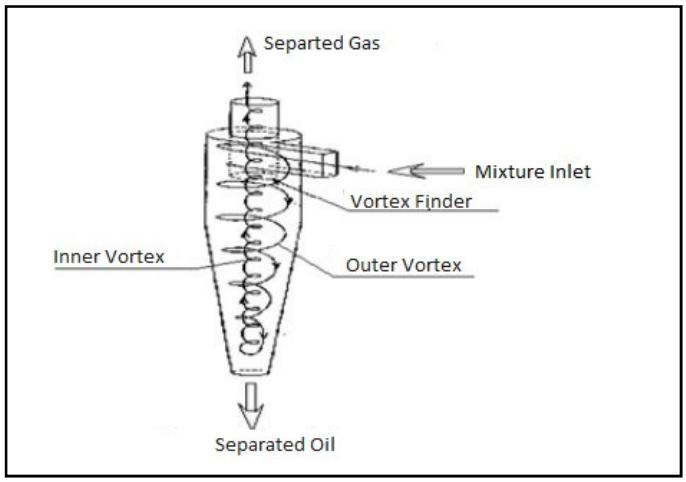


Figure- 1
Schematic working diagram of a two- phase cyclone separator

The main objective of this paper is to carry out a parametric study on various parameters which affects the performance of the cyclone separator used in automotive air conditioning systems with minimum losses. The factor which determines the separator performance is the amount of gas (refrigerant) separated from the mixture. The flow inside the separator is highly turbulent multiphase flow in which the refrigerant (CO2/R134a) to be in the primary phase and the lubricant (Poly Alkaline Glycol) which is in the secondary phase. Flow characteristics for different geometric configurations were analyzed numerically.

Methodology

Formulation of the Model: Building CFD Model: The geometrical models (surface modeling) are designed using CATIA V5 based on the parameters given in the in the figure 2 form literature[5].

The gird generated for the present study is purely tetrahedral meshes. The analysis for hexahedral mesh is also carried out but it is showing a significant variation form the values adopted form literature. Fine control over the tetrahedral mesh near the mixture inlet and oil outlet will help to capture the boundary layers more effectively. The tetrahedral mesh generated is shown in figure 3.

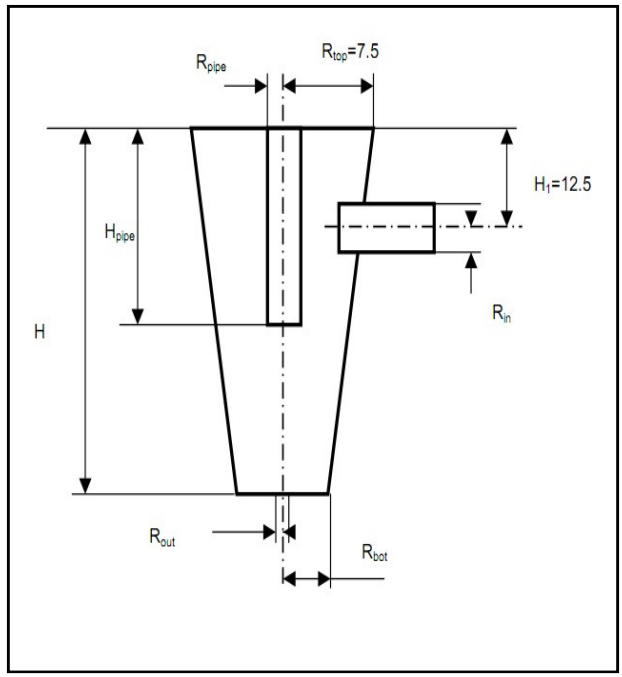


Figure -2
Schematic working diagram of a 2 phase cyclone separator (a)-(b)

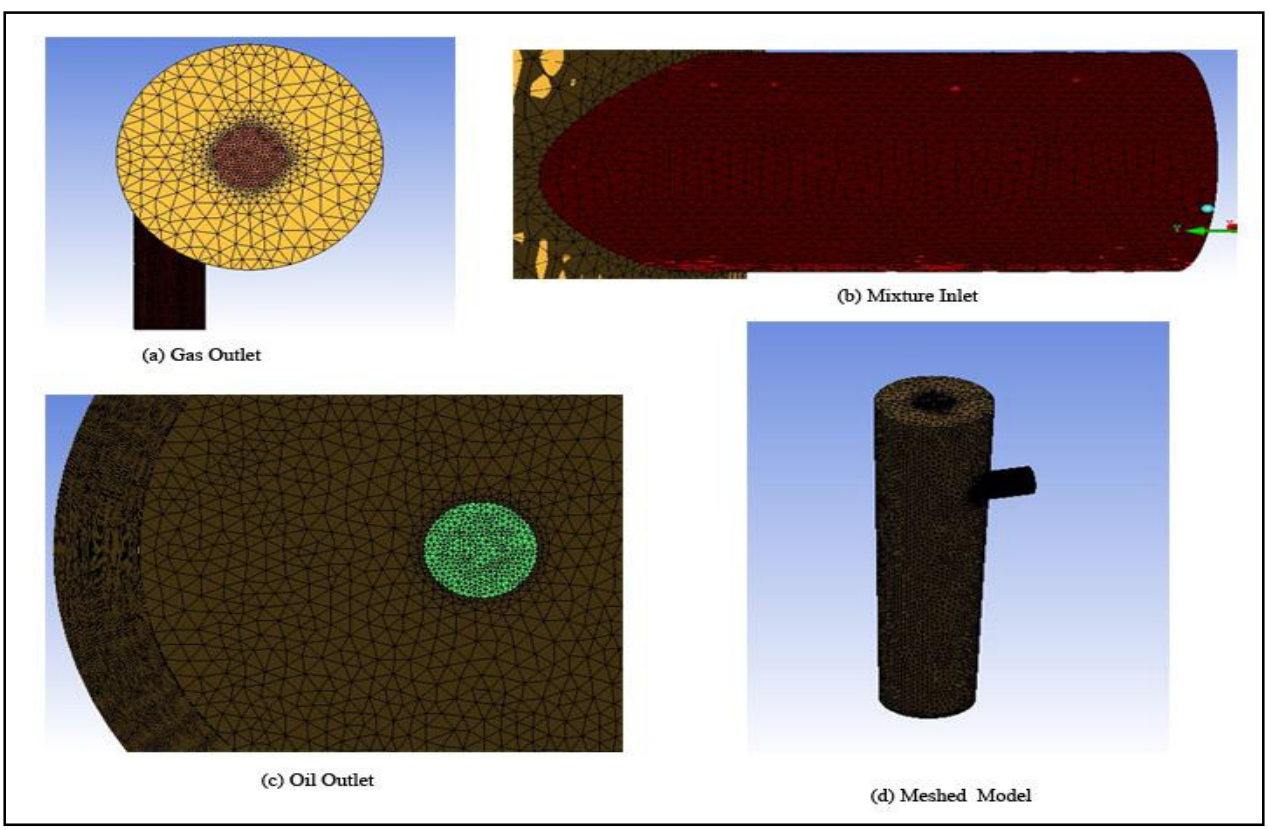


Figure- 3
Meshed model of the phase separator in discretized using ICEM CFD

Computational Fluid Models for Multiphase flow: A multiphase system is defined as a mixture of phases of solid, liquid and gas. Multiphase flows are classified according to the nature of system: dispersed flows (particle or droplets in liquid or gas, bubbles in liquid), separated flows (annular flows in vertical pipes, stratified flows in horizontal pipes) and transitional flows, which are combinations of the other two classes [5]. In this work we are focusing on multiphase flows where the secondary phases cannot be ignored due to their influence on the fluid dynamic behavior of the mixture and partly also due to their importance for the process studied. Depending on the strength of the coupling between the phases, different modeling approaches are suggested. They can be classified into homogeneous flow models, mixture models and multiphase models. Combinations of these are possible, too. In most models, each phase is treated as an interpenetrating continuum with a volume fraction parameter, which is analogous to the porosity assigned to a fluid phase in flow through a porous medium[6].

In all multiphase models, the main difficulties are due to the interfaces between the phases and the discontinuities associated to them[7]. The formulation of the constitutive equations is the greatest difficulty when developing a multiphase model for a practical application[8].

The available models for defining a multiphase flow is Discrete Phase Model, Eulerian Phase Model and Mixture model. In Discrete Phase Model (DPM) in which trajectories of particles/droplets are computed in a Lagrangian frame and have the capabilities of coupling these particles to the gas phase in the Eulerian frame. In its standard form the DPM model does not account for volume fractions of the discrete phase particles[9,10].

Considering the computation expenses and time, the discrete phase model, Eulerian Phase model is not considered for the present study. In addition to that the mixture multiphase model can give satisfactory results with less error and will account more accurately for the collision and merging effects of the oil droplets in the primary gas phase.

Multiphase Mixture Model: The continuity equation for the mixture, the momentum equation for the mixture, the energy equation for the mixture, the volume fraction equation for the secondary phases, algebraic expressions for the relative velocities (if the phases are moving at different velocities)[11].

Assumptions: i. Refrigerant and oil flows are incompressible within the oil separator; ii. There is no inter-phase mass transfer between refrigerant and oil; iii. Oil-droplets have an average diameter, which can be calculated in a weighted-average manner; iv. The mixture flow is isothermal, i.e., refrigerant and oil properties can be calculated at an average discharge pressure and temperature conditions; v. Steady state analysis is performed for the reported calculations; vi. Gravity forces are acting downward along the vertical axis of the separator body, with the regular magnitude g=9.81 m/s2

Boundary Conditions: Mixture Inlet: The inlet boundary condition involves velocity inlet along with turbulent intensity, hydraulic diameter. The velocity of air at the inlet is varied from 1 m/s to 10m/s. The volume fraction initially is taken as 0.007 and varied till 0.025.

Oil Outlet: The gas and oil outlet is designated as a pressure outlet with the operating pressure of 101325Pa.

Wall: Wall boundary conditions are enforced on all faces bounding the flow. Adiabatic, no-slip boundary conditions are applied at the walls.

Multiphase- Fluid: This boundary condition is applied to all volumes of the geometry for the fluid to flow through. Initially the separator has 100% refrigerant inside. The direction of the flow is along the axial direction.

Turbulence Model: The RNG k -ε model is selected for the present work because the effect of swirl on turbulence is included in the RNG model, enhancing accuracy for swirling flows.

Flow Solver: The phase-coupled SIMPLE algorithm with pressure spatial discretization as PRESTO!, is selected for pressure-velocity coupling while the second order scheme is employed for the discretization of the remaining equations except with volume fraction which is discretized according to First order upwind scheme

Separator Performance: Separator performance is defined by following parameters based on the steady state CFD calculation. The main aim of this work is to have maximum separator efficiency of gas and oil form the inlet . The various parameters that specify these are.

Gas separation Efficiency: $\eta_{gas} = m_{2gas}/m_{1gas}$

Liquid Separation Efficiency: $\eta_{liq} = m_{3liq}/m_{1liq}$

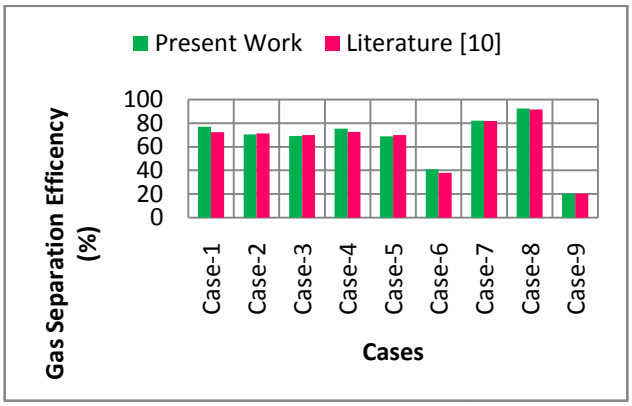
Where: $m_{2gas=}$ mass flow rate of refrigerant gas exiting through the top outlet, $m_{1gas=}$ mass flow rate of refrigerant entering the system through the inlet, $m_{3liq=}$ mass flow rate of oil droplets exiting through the bottom outlet, $m_{1liq\ =}$ mass flow rate of oil droplet entering the device.

Validation: Validation of the phase separator is carried out based on the different cases by Tiberiu Barbat, Kanwal Bhatia and Srinivas Pitla[9] is shown in table 1. The separator performance is numerically analyzed under nominal operating conditions (1 m/s inlet velocity, 0.7% liquid volume fraction at the inlet, droplet diameter d_p = 10μm) and compared with the results predicted in the literature 10. The separator efficiencies

obtained numerically is shown in figure 4. Considering the separation efficiencies of all the 9 cases maximum deviation is obtained to be 7.89%.

Table -1
Cases based on Design Parameters[10]

	R_{bot} [mm]	H_{pipe} [mm]	R_{pipe} [mm]	R_{out} [mm]
Case 1	6	30	2	1
Case 2	7.5	30	2	1
Case 3	3.125	30	2	1
Case 4	6	15	2	1
Case 5	6	40	2	1
Case 6	6	30	1	1
Case 7	6	30	4	1
Case 8	6	30	2	.5
Case 9	6	30	2	2



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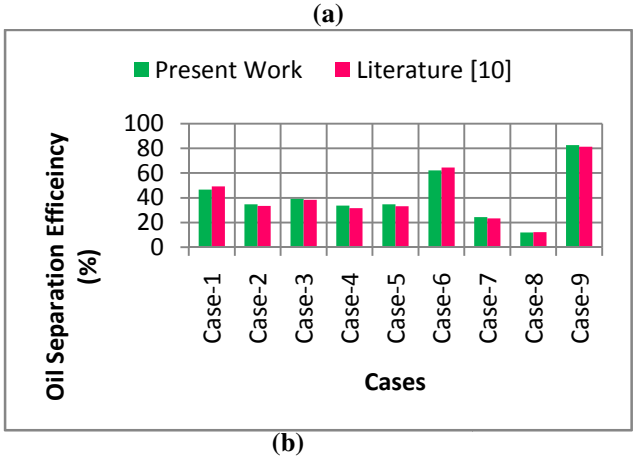
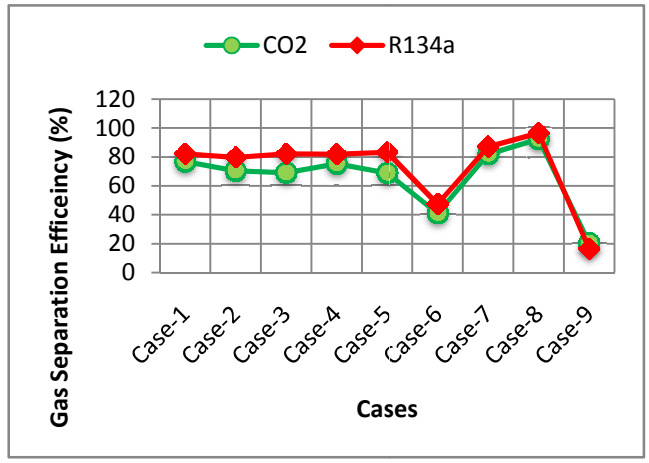


(b)

Figure – 4
Validation (a), (b)

Results and Discussions

Replacing the Refrigerant CO_2 with R134a: The refrigerant CO_2 used in the literature is not used in the market in an extensive manner[12]. The next stage in the study is to replace CO_2 with conventionally used refrigerant. It is observed form the literature by J. Steven Brown and Samuel F. Yana-Motta[13]on the performance merits of CO_2 and R134a automotive air conditioners; it is found that the COP of the refrigerating system with R134a performs better compared with CO_2. The standard properties of R134a (1,1,1,2-tetrafluroethane) is adapted from the International Journal of Refrigeration and inputted into the FLUENT V6 database[14] . The nine cases mentioned in the literature [9] are again analyzed and results are shown below.



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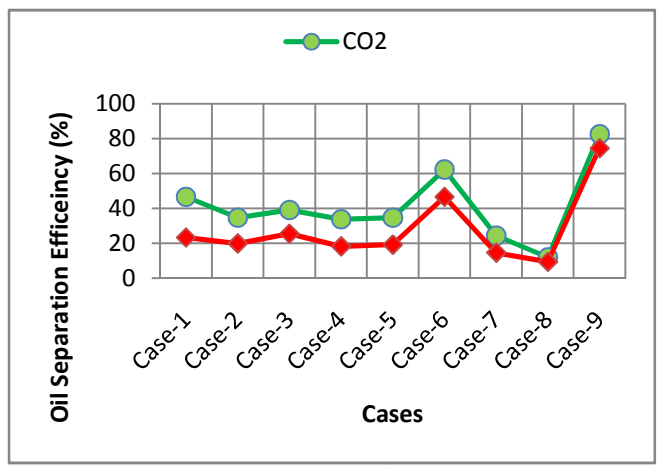


(b)

Figure- 5
Variation in Separation efficiencies (a) Shows the variation in Oil Separation efficiency for CO_2 and R134a (b) Shows the variation in Gas Separation efficiency for CO_2 and R134a

When the refrigerant CO_2 is replaced with R134a it is observed that the tendency in variation of the separation efficiency remained to be the same. The phase separator with refrigerant R134a showed an increase in gas separation efficiency with a maximum variation of nearly 21 % with that of CO_2. On the other hand the oil separation efficiency of R134a has a maximum drop of nearly 46% compared to that of CO_2 which is mainly due to change in the refrigerant properties. CFD studies on various automotive components have been carried out[15-18]

Parametric Study and Separator performance: In addition to the 9 cases mentioned above this work tries to find out the effect of other two design parameters like the height of the phase separator and mixture inlet diameter in the separator performance which extends the total number of cases to 17 and is shown in table 2. All the above cases are tested under nominal operating conditions (1 m/s inlet velocity, 0.7% liquid volume fraction at the inlet, droplet diameter $d_p = 10\mu m$) which is taken from the literature[9].

The main design parameters and its influence in separator performance are discussed below.

Radius of gas outlet(R pipe): It is clear from table 3 the gas separation efficiency considerable increases when the radius of the pipe increases from 1mm to 2mm. The main reason is as the size of the pipe increases the pressure drop will be considerably less which reduces the resistance to the flow of gas. As the radius is increased further to 4 mm, the gas separation efficiency increases further. But the chances of flow of the oil to the wrong gas outlet are more in this case; which explains the decreased oil separation efficiency.

Table -2
Additional Design Parameters under study

Cases	R_{bot} (mm)	H_{pipe} (mm)	R_{pipe} (mm)	R_{out} (mm)	H_{total} (mm)	R_{inlet} (mm)
Case 10	6	30	1	1	40	2
Case 11	6	30	1	1	45	2
Case 12	6	30	1	1	55	2
Case 13	6	30	1	1	60	2
Case 14	6	30	1	1	50	1
Case 15	6	30	1	1	50	1.5
Case 16	6	30	1	1	50	2.5
Case 17	6	30	1	1	50	3

Table -3
Separator performance in varying the radius of the pipe (R_{pipe}) (mm)

Case	R pipe mm	Gas Separation Efficiency (%)	Oil Separation Efficiency (%)
Case 6	1	47.42	46.53
Case 1	2	82.15	23.26
Case 7	4	87.16	14.53

Radius of oil outlet (R out): The dimension of the orifice at the bottom of the separator is also having a significant influence in both the separator performances. As the radius of the orifice is increased it can be perceived that the oil separation efficiency increases due to reduction in pressure drop in the oil path which results in more oil separation. This will allow more refrigerant to pass through the oil outlet that results in decreased gas separation efficiency. Table 4 shows the increase in oil separation efficiency and decrease in gas separation efficiency as the radius of the oil outlet orifice is increased.

Table-4
Separator performance in varying the radius of oil outlet (R_{out}) (mm)

Case	R out mm	Gas Separation Efficiency (%)	Oil Separation Efficiency (%)
Case 8	.5	96.6	9.3
Case 1	1	82.15	23.26
Case 9	2	16.31	74.45

Radius of separator bottom (R bot): This parameter is primarily responsible for the shape of the phase separator. Table 5 shows that the variation in the separator bottom radius, it can be observed that nearly 3% variation in both separator efficiencies. This implies that the variation in radius of the separator bottom has literally negligible influence in the separator performance

Radius of mixture inlet (R in): This parameter is primarily responsible for the amount of mixture which is going into the phase separator. Observing table 6 it is possible to infer that the influence of mixture inlet in separator performance is not significant when compared with the above discussed factors. As the radius increases more and more refrigerant gas will be incident into the separator this will result in increased flow of gas to the gas outlet which explains the slight increase in the gas separation efficiency.

Table-5
Separator performance in varying the radius of separator bottom(R_{bot}) (mm)

Case	R bot mm	Gas Separation Efficiency (%)	Oil Separation Efficiency (%)
Case 3	3.125	82.13	25.46
Case 1	6	82.15	23.26
Case 2	7.5	79.68	19.82

Table-6
Separator performance in varying the radius of mixture inlet (R in) (mm)

Case	R in mm	Gas Separation Efficiency (%)	Oil Separation Efficiency (%)
Case 14	1	30.23	66.12
Case 15	1.5	36.46	65.98
Case 16	2.5	40.74	62.43
Case 17	3	42.33	61.25

Height of the gas outlet pipe (H pipe): Changing the height of the gas outlet pipe showed a negligible variation in the separator performances. This implies that the influence of gas outlet pipe in the separator performance is not significant and this design parameter can be anywhere in the range given in table 7.

Table-7
Separator performance in varying the Height of the gas outlet pipe (H_{pipe})

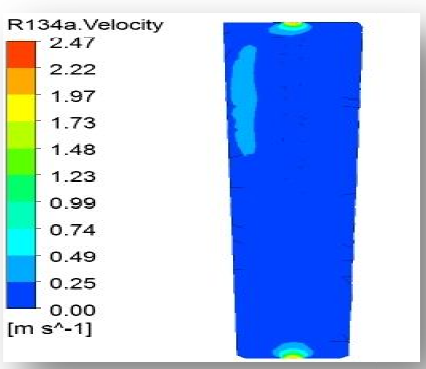
Case	H pipe mm	Gas Separation Efficiency (%)	Oil Separation Efficiency (%)
Case 4	15	81.87	18.16
Case 1	30	82.15	23.26
Case 5	40	83.25	19.14

Overall Height of the pipe (H): The final design parameter which was considered under the present study is the overall height of the phase separator. Numerical simulations are carried out for various values of phase separator height and are shown in Table 8. It is observed that the gas separation efficiency remains almost constant as the value of H increases. On contrary to that the value of oil separation efficiency first increases up to a certain value of H and then decreases. This is because as the length of the pipe is more, the chances length of the vortex inside the separator will be more and as a result, more oil can get separated inside the phase separator up to a certain limit.

Table -8
Separator performance in varying the height of the separator (H) (mm)

Case	H mm	Gas Separation Efficiency (%)	Oil Separation Efficiency (%)
Case 10	40	52.82	40.95
Case 11	45	51.52	47.13
Case 12	55	52.3	52.54
Case 13	60	53.45	38.74

Flow Pattern obtained from CFD Analysis: Figure 6 shows the velocity contour in a multiphase flow for R134a and PAG taken along the mid plane of the phase separator. It can be seen that velocity of R134a is more compared to that of PAG oil. The velocity is remaining almost constant inside the separator body. The velocity increases as the oil/gas moves towards the exit.



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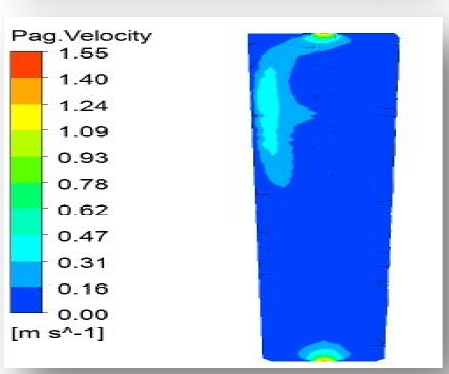


(b)

Figure - 6
Case 6 Velocity contours for (a) R134a and (b) PAG

Figure 7 shows the streamline flow pattern obtained for the mixture. It is clear that a swirling motion is present inside the phase separator which is responsible for the separation of R134a and PAG oil.

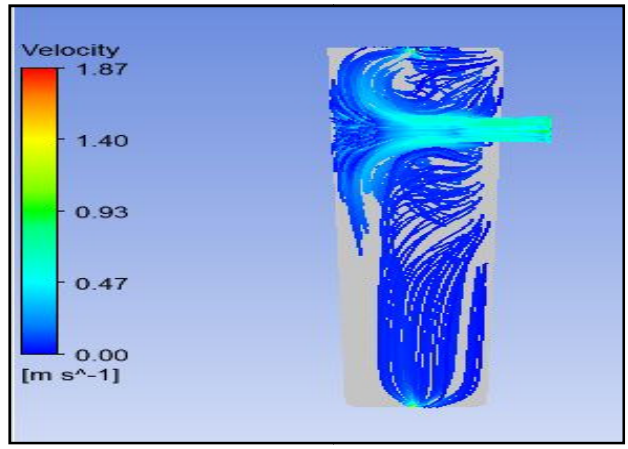
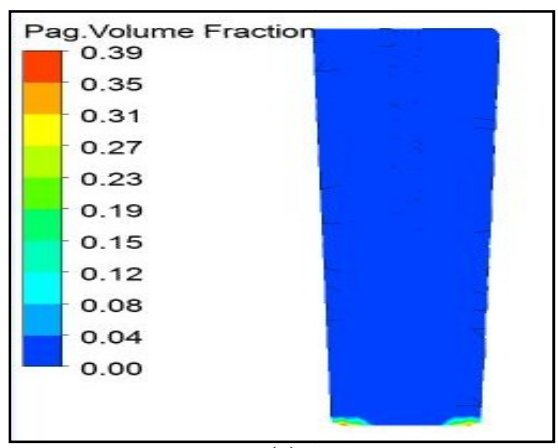


Figure -7
Case 6 Streamline flow of the mixture at 1m/s inlet velocity

Figure 8 displays the Volume fraction of R134a and PAG in the same axial cut in the nominal operating conditions. It is clear that the PAG volume fraction is very low compared to that of R134a and PAG oil is found to be towards the oil exit.



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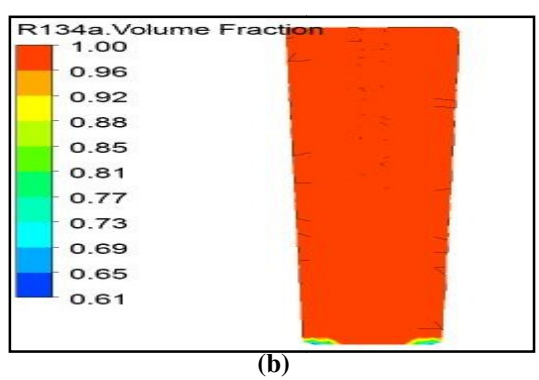

(b)

Figure -8
Case 6 Volume fraction for (a) R134a and (b) PAG

Conclusion

In the automotive systems, use of a phase separator after the compressor can increase the COP of air-conditioning system as it improves the working of the heat exchanger. A separator's performance is analyzed using the oil separation efficiency and gas separation efficiency.

When the refrigerant CO_2 is replaced with commercially available R134a it is observed that the trend in variation remains the same. But the oil separation efficiency dropped to nearly 50 %. , though the gas separation efficiency is reported to have an increase in value. The main reason is because of the change in properties of refrigerant.

Multiphase flow of different geometrical models, meshes and numerical models are built and run using parametric journal files. Numerical simulation shows that among the six design parameters selected, the radius of the pipe (R_{pipe}) and Radius of the oil outlet (R_{out}) is having a significant influence in the performance of the phase separator. A slight variation in the above parameters can drastically alter the oil separation efficiency and gas separation efficiency. The remaining four design parameters shows that they are having negligible influence in the separator performance compared with the above two parameters.

The oil separation efficiency and gas separation efficiency for a particular parameter cannot hold a higher value in both cases. There should be a satisfactory compromise between the two. In the total 17 design parameters discussed in the paper, it is observed that Case 6 and Case 12 fall under such a case. Their separator efficiencies are found to be nearly 50 % in both the cases which is required.

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