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Research Paper

CFD MODELLING OF FINNED TUBE GAS COOLER FOR TRANSCRITICAL OPERATOON OF CO_2 SYSTEMS

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Refrigerators and heat pumps plays an important role in this modern world. Refrigerants are used as working fluid in the thermal systems. These refrigerants undergo phase change in evaporator to provide a cooling effect. Chlorofluorocarbons and Hydroflurocarbons are the commonly used refrigerants but their stability in the atmosphere and their effect on GWP and ODP is a concern. Because of the harmful effects of synthetic refrigerants on the environment, industries are now looking for technologies based on natural refrigerants. Because of non-toxicity, high availability in nature and some unique thermo-physical property CO_2 is considered as the replacement for synthetic refrigerants. This facts motivated many and has lead to the development of trans critical cycle where the condenser gets replaced by a gas cooler. Use of the gas cooler with heat rejection taking place with large temperature glide offers several unique possibilities such as such as simultaneous cooling and heating, heat pump drying, water heating, etc. Main difference of CO_2 with other refrigerants is its low critical temperature. However this gives an advantage of high volumetric capacity, which makes the CO_2 systems more compact. Initially micro-channel heat exchangers are suggested as gas coolers for CO_2 systems, but its high manufacturing cost makes it economically non-feasible. The objective of this work is to carry out CFD studies on finned tube gas cooler for transcritical operation of CO_2 systems. Flow pattern, Temperature distribution and performance variations with different operating conditions (mass flow rate of CO_2, air velocity, etc.) are studied and validated by test data obtained from the literature.

Keywords: CO_2, Gas cooler

INTRODUCTION

Two international agreements Montreal Protocol and Kyoto Protocol were introduced to reduce the problem of ozone layer depletion and global warming. The Montreal Protocol was introduced in September 1987 to phase-

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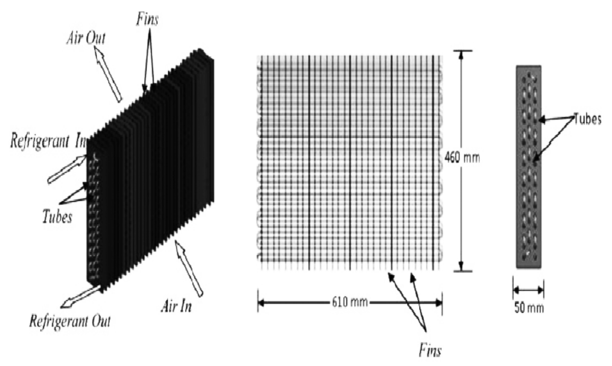
out the use of Ozone Depleting Substances. Ozone Depleting Potential (ODP) is the fraction of the ozone depleting potency of a substance compared to that of R11 or R12. The Kyoto Protocol was introduced at the third conference of United Nations Framework Convention on Climate Change (UNFCCC) in December 1997, which has imposed restrictions on refrigerants on the basis of GWP. Global warming Potential (GWP) is an index that relates the amount of gas trapped by a greenhouse gas to that of CO_2 over a 100-year period. The CFC refrigerants, although once considered to be the best refrigerants, were abandoned due to high ODP. In this situation, industries are looking for long-term solution for refrigerant related problems. This has triggered a large number of studies to develop new technologies. Instead of continuing search for new refrigerants, there is an increasing interest in technologies based on natural refrigerants. Natural Refrigerants are those substances which are already there in large quantity in the biosphere and which we know as harmless. Because of non-toxicity and non-flammability, carbon dioxide offers both environmental and personal safety. Carbon dioxide (CO_2), has been attracting more and more attention in the HVAC industry. Compared with the conventional refrigerants like R22, R134a and R404A, CO_2 is more Eco friendly with zero ozone-depleting potential and very low direct global warming potential. Along with eco-friendliness, CO_2 based systems have various advantages over conventional systems such as, compatibility with normal lubricants, common machine construction materials, non-flammability, non-toxicity, high volumetric refrigerant capacity, reduced compression ratio, easy availability and excellent heat transfer properties. However, CO_2 has a quite high operating pressure because of its low critical temperature (31.1 °C) and high critical pressure (73.8 bar). In a CO_2 refrigeration system when heat is rejected to ambient air at temperatures or above 31.1 °C (critical temperature of CO_2) the refrigeration cycle is said to operate in a transcritical state. The conventional air-cooled condenser is therefore replaced with a gas cooler. CO_2 cycle offers several unique applications such as simultaneous heating and cooling, high temperature heating and space heating, etc.

Even though there have been considerable prior research done in the area of cycle analysis and application areas, there appears to be some untouched areas like CFD analysis, flow modelling etc. Many research works have done on the possibility of using micro-channel heat exchangers as Gas Cooler for CO_2 systems. However the design and manufacturing of micro channel gas cooler requires huge investment. Because of this, its use is limited to high end applications only. So many researchers are working on the possibility of using finned tube heat exchanger as a gas cooler for transcritical operation of CO_2 systems. This work is concerned with the CFD analysis of the finned tube gas cooler for transcritical operation of CO_2 systems. Finned tube gas cooler with smooth internal surface have been simulated to study its performance.

METHODOLOGY

An identical gas cooler geometry as used by used by Hwang *et al.* (2005) (Figure 1) is selected for CFD modeling. A periodic section

Figure 1: Finned Tube Gas Cooler



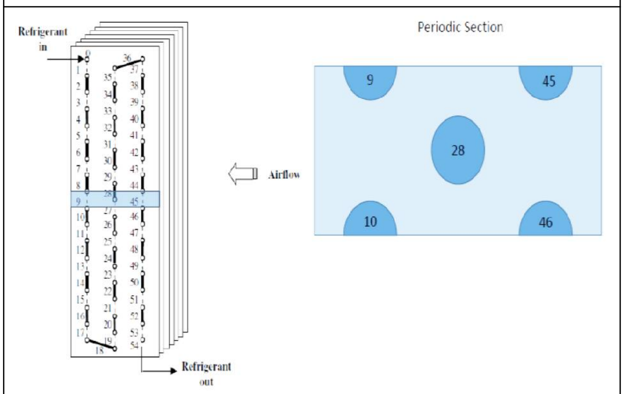
Source: Pettersen (1997)

Table 1: Specification of Tested Gas Cooler

Width × Height × Depth	610 × 460 × 50 mm^3
Front area	610 × 460 mm^2
Fin (plate type)	
Material	Aluminum (K = 250 W m^{-1} K^{-1})
Pitch	1.5 mm
Thickness	0.13 mm
Tube (circular and smooth)	
Number of row	3
Number of tube per row	18
Outside diameter	7.9 mm
Inside diameter	7.5 mm
Material	Copper (K = 385 W m^{-1} K^{-1})

five tubes in the middle of the heat exchanger as shown in Figure 2 is and I used to evaluate the performance of finned tube heat exchanger for the trans-critical operation of CO_2. This simplification helped to reduce the overall count of the mesh. Also it gives the freedom to go for more fine and good quality mesh which will help to get to better results.

Figure 2: Simplification of Actual Geometry



CFD DOMAIN AND BOUNDARY CONDITIONS

Domain has been simplified as discussed above and the CAD model for the same is developed using solidworks 2012. To reduce the mesh count only three fins are modelled, two monitor planes are created between first and second fins, between second and third fins and temperature drop between this monitor planes are used as a parameter to judge the performance of the geometry. For the flow to become full developed before entering the CFD domain CO_2 is allowed to flow through a tube without fins. This tube walls are modelled as adiabatic walls so that only turbulence and flow equation will come to the picture for the flow of CO_2 outside the actual CFD domain. Fins and tubes are modeled as surfaces and thickness is given by using shell conduction option in fluent.

An enclosure is made which is covering this arrangement and sufficient length is provided to avoid the possibility of reverse flow. Considering the small gap between each fins normal tetrahedron mesh may not be sufficient for effectively capturing the flow. So wedge (prism mesh with triangular base) mesh is created for the geometry using ICEM CFD 14. Variable height hexahedral mesh is used near the tube surface for effectively capturing the boundary layer formation. First cell height for the same is calculated based on y+ criteria. Once the meshing is done mesh file is imported to fluent 14 boundary conditions are applied to the parts and it is solved for Flow,

Table 2: Boundary Conditions

S. No.	Parts	Type of Boundary Condition
1.	Air Inlet	Velocity Inlet
2.	Air Outlet	Pressure outlet
3.	CO_2 Inlet	Mass flow inlet
4.	CO_2 Outlet	Pressure outlet
5.	Enclosure Sides	Symmetry
6.	Monitor Surfaces	Interior
7.	Fins, Tubes	Wall

solution is converged it is solved for turbulence and then for energy equation. Solution is said to be converged when then the energy residuals are in the range of 10^{-10} and other residuals in the range of 10^{-5}. Also flatness CO_2 temperature monitors, y+ value, mass and energy balance are also considered to check the correctness of a solution obtained.

Table 3: CFD Result (V_a =1 m/s, T_{atm} = 29.4 °C)

tube no	monitor_in	monitor_out	diff	predicted temp drop for full tube(degre cel)	temp drop predicted for the full tube by Y.T. Ge (degre cel) [1]	actual temp drop for the full tube(degre cel) [19]	percentage error_CFD(%)	percentage error_Y.T. Ge(%)	Average Temp drop per fin
9	60.9684	60.95188	0.016514	3.401884	2.53	3.29	-3.400729483	23.10030395	
10	57.97616	57.96371	0.012451	2.564906	2.53	2.53	-1.379683794	0	
28	43.00233	43.0034	-0.00107	-0.220832	0.1428	-0.214	-3.192523365	166.728972	0.007186
45	41.49896	41.4985	0.000458	0.094348	0.133	0.133	29.06165414	0	
46	41.29908	41.29868	0.000393	0.080958	0.133	0.133	39.12932331	0	

Turbulence and Energy Equations. For the first simulation identical conditions as given by Ge and Cropper (2009) is used and this results are used to validate the model.

An open source data base called COOL-PROP is used to find the property values of CO_2 at different temperatures. A simple code is developed in MATLAB for this purpose. After defining boundary conditions monitors are set to monitor convergence of temperature CO_2 at monitor planes. From literatures it is fond that $k–\varepsilon$ model is will give better turbulence modeling for fin and tube heat exchanger. So for better accuracy $k–\varepsilon$ realistic algorithm is used to model turbulence flow of CO_2 in tubes.

Calculations are run till the solution get converged. First only the flow equation is considered for the calculation. Once the

Figure 3: Temperature Contour of Air When Inlet Air Velocity is 1 m/s, 2 m/s and 3 m/s Respectively(T_{atm} = 29.4 °C)

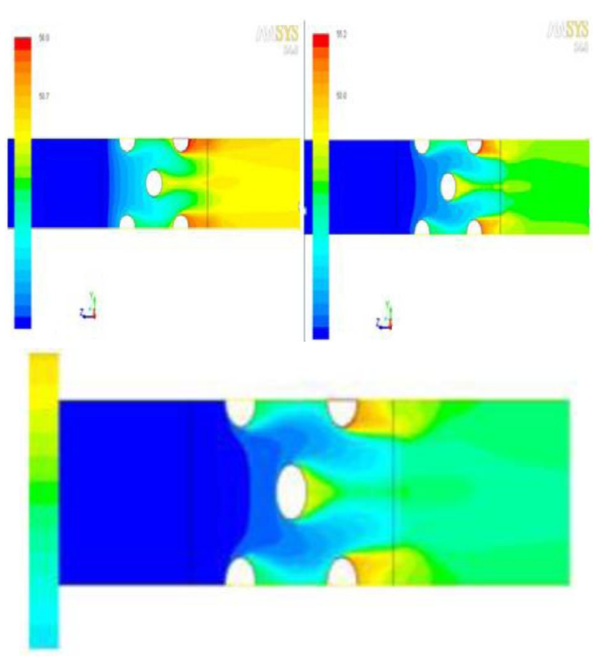


Figure 4: Velocity Contour of Air When Inlet Air Velocity is 1 m/s, 2 m/s and 3 m/s Respectively (T_{atm} = 29.4 °C)

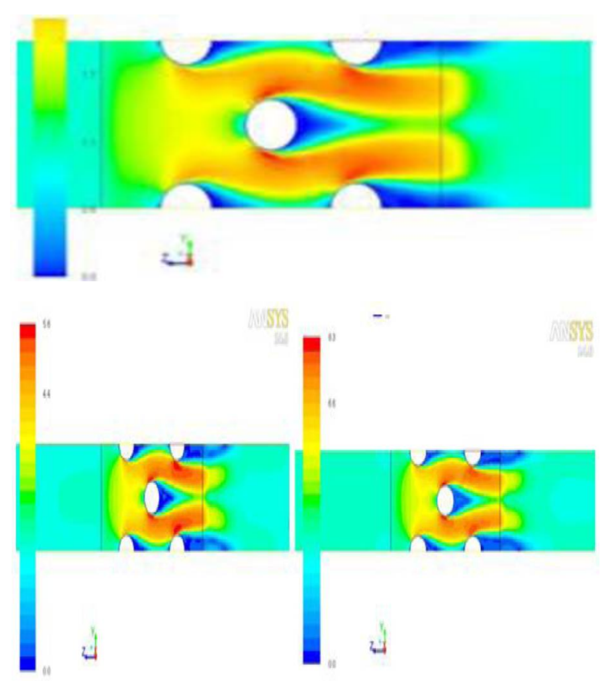
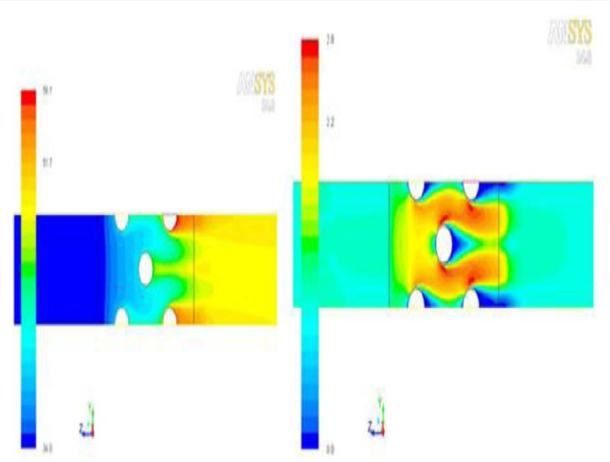


Figure 5: Temp and Velocity Contour of Air When T_{atm} is 34 °C (Inlet Air Velocity = 1 m/s)



RESULTS AND DISCUSSION

The obtained result compared with previously published experimental and simulation result. The CFD results obtained are found to have close matching with experimental result.

The contours displayed in Figures 3 to 5 reveal the temperature increases in the fluid due to heat transfer from the tubes. The hotter fluid is confined to the near-wall and wake regions, while a narrow stream of cooler fluid is convected through the tube bank. The consequences of different air velocity to the fluid temperature distribution are shown in the above figures. When the fluid through the bank of tubes the maximum velocity occur at either the transverse plane or the diagonal plane where the flow area is minimum. The velocity vectors displayed in Figure 3 reveal that the CFD results show very low velocity values adjacent to the tube surface. In the regimes between the tubes, i.e., at the transverse plane the maximum velocity was occurred.

CONCLUSION

CFD gave better results than the Mathematical simulation done by Ge and Cooper(2009) . Effect of eddies formation and flow separation are found to be increasing with air velocity. Flow separation was maximum when air velocity in 2 m/s. There was not much change in this behavior with the change in atmospheric temperature. Temperature of the CO_2 which is flowing through the middle tube is found to be increasing slightly. This is because of the high temperature of CO_2 flowing through nearby tubes. This problem can be overcome by providing more pitch or more air velocity. Temperature profile and velocity profile air was more smoother at higher velocities of air.

REFERENCES

1. Bullard C (2004), "Transcritical CO_2 Systems e Recent Progress and New

Challenges Review Article", *Bull. IIF-IIR*, Vol. 84, No. 5, pp. 6-19.

2. Ge Y T and Cropper R T (2009), "Simulation and Performance Evaluation of Finned-Tube CO_2 Gas Coolers for Refrigeration Systems", *Applied Thermal Engineering*, Vol. 29, pp. 957-965.

3. Giannavola M, Murphy R, Yin J, Kim M H, Bullard C and Hrnjak P (2000), "Experimental Investigations of an Automotive Heat Pump Prototype for Military", SUV and Compact Cars, The 4th IIR-Gustav Lorentzen Conference on Natural Working Fluids, pp. 115-122, West Lafayette, IN.

4. Hwang Y, Jin D D H, Adermacher R and Hutchins J W (2005), "Performance Measurement of CO_2 Heat Exchangers", ASHRAE Transactions, pp. 306-316.

5. Lorentzen G (1994), "Revival of Carbon Dioxide as a Refrigerant", *International Journal of Refrigeration*, Vol. 17, No. 5, pp. 292-301.

6. Nilam P Jadhav (2012), "Numerical Simulation of Fin and Tube Gas Cooler for Transcritical CO_2 Air Conditioning System", *International Journal of Engineering Research & Technology (IJERT)*, Vol. 1, No. 10.

7. Neksa P, Rekstad H, Zakeri G R and Schiefloe P A (1998), "CO_2-Heat Pump Water Heater: Characteristics, System Design and Experimental Results", *International Journal of Refrigeration*.

8. Pettersen J (1997), "Experimental Results of Carbon Dioxide in Compression Systems", ASHRAE-NIST Refrigerant Conference, Proceedings, October, pp. 27-37.

9. Sarkar J, Bhattacharyya S and Ramgopal M (2004), "Optimization of a Transcritical CO_2 Heat Pump Cycle for Simultaneous Cooling and Heating Applications", *International Journal of Refrigeration*, Vol. 27, No. 8, pp. 830-838.

10. Yang Chen (2006), "Analysis of Supercritical Carbon Dioxide Heat Exchangers in Cooling Process", International Refrigeration and Air Conditioning Conference.

11. Yarral M G, White S D, Cleland D J, Kallu R D S and Hedley R A (1999), "Performance of Transcritical CO_2 Heat Pump for Simultaneous Refrigeration and Water Heating", 20th International Congress of Refrigeration, p. 651, IIR/IIF, Sydney.

12. Young-Soo Chang and Min Seok Kim (2005), "Modeling and Performance Simulation of a Gas Cooler for a CO_2 Heat Pump System", HVAC&R Research, May.