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EFFECT OF OPERATING PARAMETERS ON THE PERFORMANCE OF FIN AND TUBE GAS COOLER FOR TRANS-CRITICAL OPERATION OF CO_2 HEAT PUMPS

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ABSTRACT

Environmental concern has become more significant and motivating factor in recent times in design and development of any domestic or industrial products. Consumers have become increasingly aware of the environment and the need to preserve the world in which all live. Concern about ozone depletion has led to the abolition of the use of chlorofluorocarbons (CFCs) and hydro chlorofluorocarbons (HCFCs) as refrigerant. Much of the researchers were reported about the advantage of using CO_2 in trans-critical state. Use of a gas cooler, with heat rejection taking place over an unusually large temperature glide, offers several unique possibilities such as simultaneous refrigeration and heating, heat pump drying, etc. CFD model a finned tube gas cooler for transcritical operation of CO_2 system was developed using ANSYS Fluent 14 to study the effect mass flow rate of CO_2, fin thickness and tube thickness on the performance of gas cooler. Flow pattern, Temperature distribution and performance variations with different operating conditions were also studied and the obtained results were validated by test data obtained from the literature. Results shows that the performance of the gas cooler is greatly influenced to the changes in mass flow rate of CO_2 and fin thickness. Performance of the gas cooler is not that affected by the tube thickness. Temperature drop per fin is found to be decreasing with mass flow rate of CO2 and tube thickness whereas it is fund to be increasing with fin thickness. Temperature drop varies parabolically with tube thickness and fin thickness whereas mass flow had almost a linear relation with temperature drop.

Keywords: CO_2, CFD, Gas -Cooler, Trans-critical cycle

I. INTRODUCTION

In today's scenario, environmental concern has become a major issue and motivating factor in the design and development of domestic thermal appliances and industrial products. Consumers are now increasingly concerned about the environmental issues caused by the wastages and the pollutants which are damaging the ozone layer of the environment. There is great awareness among the consumers about the need to preserve ozone layer of the planet. This preservation of ozone layer is needed for human life survival on the earth. It is a challenging research work to developing energy efficient products for domestic and industrial applications with the concern on ecological aspects. Thermal system products like refrigeration and heat pump systems are also not an exception from this ecological concern and it need to be explored and analysed. More than 33% of total power generated is now been consumed in refrigeration and air conditioning sector. At present in India 7 to 8 million installed small capacity air conditioning systems are working and consuming whooping 14 to 15 thousand MWHR of electrical energy per day.

The Kyoto protocol has forced many industries to come up with more environmental friendly solutions. Because of this industries started to spend more money to sponsor R&D projects to develop new and improved refrigerants which cause minimum damage to the environment. This has led many researchers and practitioners to concentrate more on natural refrigerant based refrigeration systems.

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 CO2 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 CO2 systems. This work is concerned with the CFD analysis of the finned tube gas cooler for transcritical operation of CO2 systems. Finned tube gas cooler with smooth internal surface have been simulated to study its performance.

II. METHODOLOGY

It has been observed that the synthetic refrigerants are very harmful to the ecological system in which we live, so the industries are now looking for eco-friendly refrigerants which can replace the synthetic refrigerants. Out of the commonly used natural refrigerants CO2 has got some unique advantages and applications because of its some special thermo physical properties. This forced many researchers and practitioners to work on trans critical cycle of CO2 . This studies has shown that the overall performance of the trans critical cycle is greatly influenced by the performance of gas cooler. Even if many types of gas coolers were proposed for transcritical operation of CO2 systems, many researchers have reported that fin and tube type gas cooler is more economical than other types of gas coolers. The purpose of this paper is to investigate the performance of the gas cooler which works on transcritical cycle by using CFD software ANSYS FLUENT 14.0 and to identify the effect of fin thickness, tube thickness and mass flow rate of CO2 on the performance of gas cooler. For this a fin and tube gas cooler (Fig: 1) with specifications as in Table 1 was modelled and simulated in ANSYS FLUENT 14.0 double precision solver.

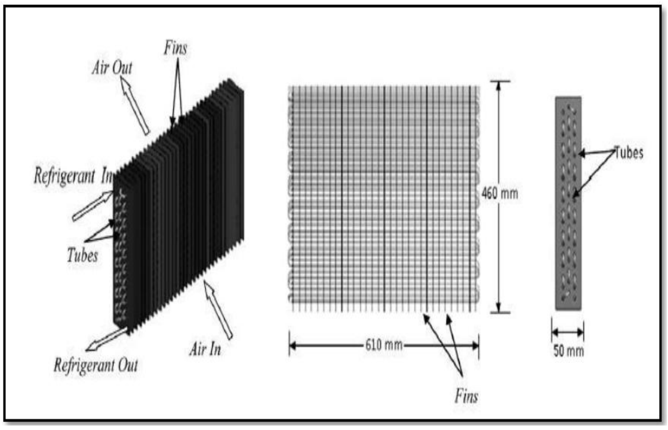


Figure 1: Finned tube gas cooler [5]

Table 1: Specification of the gas cooler.

Width ×Height ×Depth	610×460×50 mm^2
Front Area	610 ×460 mm^2
Fin Material	Aluminum (K=250 W m^{-1} K^{-1})
Pitch(Fin)	1.5 mm
Thickness	0.13 mm
No of tube rows	18
Outside diameter of the tube	7.9 mm
Inside diameter of the tube	7.5 mm
Tube Material	Copper (K=385 W m^{-1} K^{-1})

An identical gas cooler geometry as used by used by Y.T. Ge [10] is selected for CFD modeling. A periodic section five tubes in the middle of the heat exchanger as shown in fig 3.2 is used to evaluate the performance of finned tube heat exchanger for the trans-critical operation of CO2.

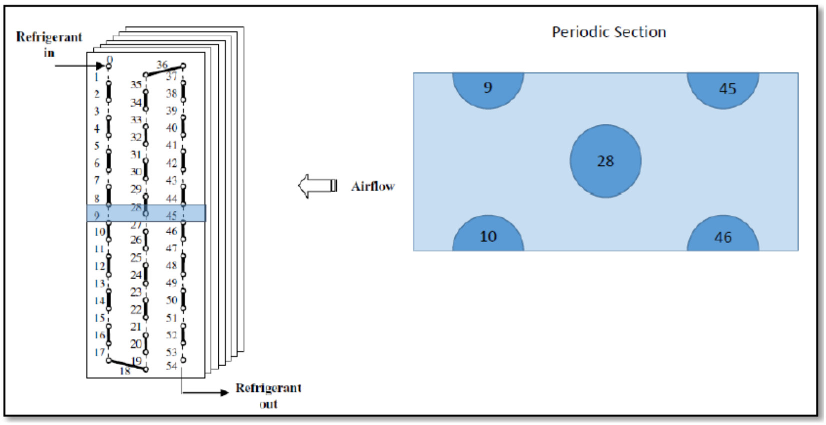


Figure 2: Simplification of geometry

A simple three-dimensional model the gas cooler was developed using SOLIDWORKS, a commercial CAD software package and meshing is done using ICEM CFD. Wedge type mesh elements are used for accurate results. A simple three-dimensional model the gas cooler was analyzed using ANSYS FLUENT 14.0, a commercial computational fluid dynamics software package, to examine airflow and temperature distribution under different circumstances.

III. CFD MODEL

The CFD software, ANSYS FLUENT 14.0, was set up to use the following equations to resolve the flow and temperature distributions of the gas cooler: flow, heat transfer, and turbulence. Each of these model has its own set of governing equations and is discussed below.

3.1 Flow Model

The flow model was used to determines the velocity and pressure fields by solving conservation equations. Flow model consist of laws of conservation of mass and momentum, which lead to the use of the Navier-Stokes equations to obtain the flow solutions. The following sections describe the governing flow equations.

3.1.1Mass Conservation Equation

The law of conservation of mass is applied to the control volume. The time rate of change of mass in the control volume must be balanced by the difference between the mass exiting and entering the control volume. This principle is described by the equation below.

$$\frac{\partial \rho}{\partial t} + \nabla \bullet \left(\rho \vec{V} \right) = 0 \qquad \text{(eqn.1)}$$

where ρ is the air density and $\vec{V}$ is the velocity vector. The first term on the left expresses the time rate of change of density while the second term describes the net mass flow through the control volume.

3.1.2 Momentum Conservation Equations

The law of conservation of momentum states that the time rate of change of momentum of a fluid element is equal to the sum of the forces acting on the element. The equation below describes the three-dimensional x-component of this principle.

$$\frac{\rho Du}{Dt} = \frac{\partial(-p + \tau xx)}{\partial x} + \frac{\partial \tau yx}{\partial y} + \frac{\partial \tau zx}{\partial z} + SMx \qquad \text{(eqn. 2)}$$

where u is the fluid velocity in the x-direction, v is the fluid velocity in the y-direction, w is the fluid velocity in the z-direction p is the pressure, µ is dynamic viscosity. Similarly the following equations describes the three-dimensional y-component and z-component of this principle.

$$\frac{\rho Dv}{Dt} = \frac{\partial(-p + \tau yy)}{\partial y} + \frac{\partial \tau xy}{\partial y} + \frac{\partial \tau zy}{\partial z} + SMy \qquad \text{(eqn. 3)}$$

$$\frac{\rho Dw}{Dt} = \frac{\partial(-p + \tau zz)}{\partial z} + \frac{\partial \tau yz}{\partial y} + \frac{\partial \tau xz}{\partial x} + S\,Mz \qquad \text{(eqn .4)}$$

3.2 Navier-Stokes Equations

To further develop the momentum equations given above, the variable viscous stresses components are expressed as function of local deformation rate and simplifying yields Navier Stokes equations

$$\rho \frac{Du}{Dt} = -\frac{\partial p}{\partial x} + div(\mu \, grad \, u) + SMx \quad \text{(eqn .5)}$$

$$\rho \frac{Dv}{Dt} = -\frac{\partial p}{\partial y} + div(\mu \, grad \, v) + SMy \quad \text{(eqn .6)}$$

$$\rho \frac{Dw}{Dt} = -\frac{\partial p}{\partial z} + div(\mu \, grad \, w) + SMz \quad \text{(eqn .7)}$$

3.3 Turbulence Model

The CFD program was set to use a realizable k-epsilon model for turbulence. The realizable k-ε model is a recent development and differs from the standard k-ε model in two important ways.

- The realizable k-ε model contains a new formulation for the turbulent viscosity.
- A new transport equation for the dissipation rate, ε , has been derived from an exact equation for the transport of the mean-square vorticity fluctuation.

The model is called as "realizable" as it satisfies certain mathematical constraints on the Reynolds stresses, consistent with the physics of turbulent flows. Neither the standard k-ε model nor the RNG k-ε model is realizable. Benefit of the realizable k-ε model is that it predicts the flow behaviour more accurately. It is also reported to provide better performance for flows involving rotation, boundary layers under strong adverse pressure gradients, separation, and recirculation than standard k-ε model.

The realizable k-ε models has shown substantial improvements over the standard k-ε model where the flow features include strong streamline curvature, vortices, and rotation. Initial studies have shown that the realizable model provides the best performance of all the k-ε model versions for several validations of separated flows and flows with complex secondary flow features.

One of the weaknesses of the standard k-ε model or other traditional k-ε models lies with the modelled equation for the dissipation rate (ε). The well-known round-jet anomaly (named based on the finding that the spreading rate in planar jets is predicted reasonably well, but prediction of the spreading rate for axi-symmetric jets is unexpectedly poor) is considered to be mainly due to the modelled dissipation equation.

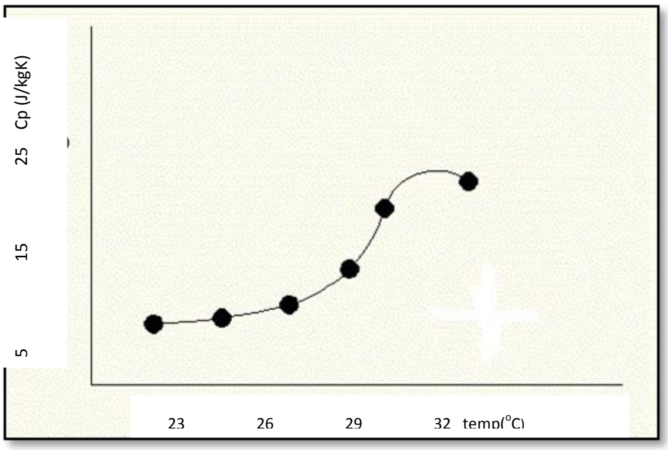
The realizable k-ε model proposed by Shih et al. was intended to address these deficiencies of traditional k-ε models by adopting the following [Fluent Theory guide, 2013]

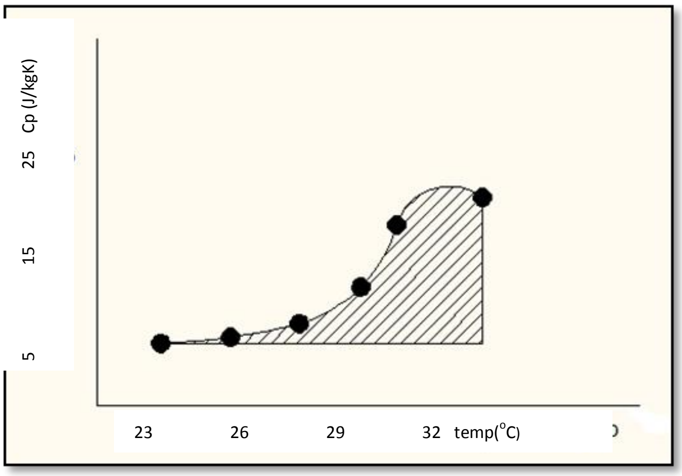
- A new eddy-viscosity formula involving a variable C_μ originally proposed by Reynolds].
- A new model equation for dissipation (ε) based on the dynamic equation of the mean-square vorticity fluctuation.

One limitation of the realizable k-ε model is that it produces non-physical turbulent viscosities in situations when the computational domain contains both rotating and stationary fluid zones. This is due to the fact that the realizable k-ε model includes the effects of mean rotation in the definition of the turbulent viscosity. This extra rotation effect has been tested on single rotating reference frame systems and showed superior behaviour over the standard k-ε model. [Fluent Theory guide, 2013]

3.3 Thermo Physical Properties of CO_2

Thermo physical properties of CO_2 will vary widely near the critical point. This makes the modeling and design of gas cooler extremely difficult.One method to resolve this difficulty is to split it into number of heat exchangers connected in series. This is the method used in all the reported researches till now to consider the effect of in variations thermo physical properties. But this is a very complex process and this method not is suitable for CFD. For overcoming this problem simple code [Appendix 1] is developed in MATLAB to find the mean values of specific heat, density and dynamitic viscosity of the thermo-physical properties of CO_2 over the temperature range. For this property values are taken from the open source data base COOLPROP. To avoid the difficulties because of the large variations the thermo-physical properties in the transcritical region,mean property values are used instead of using property values at mean temperature for this simulation.





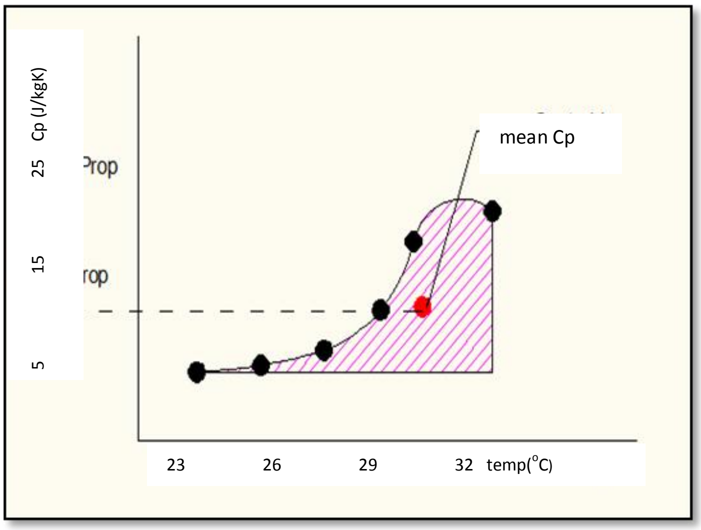


Figure 3: Mean variation of the thermo-physical properties

IV. RESULTS AND DISCUSSIONS

CFD model was created and simulated by using commercial software ANSYS FLUENT 14.0 by varying the parameters air velocity, atmospheric temperature, refrigerant mass flow rate, tube thickness, ambient temperature and fin thickness. Different plots like velocity vector, temperature contour were also plotted. The obtained result were compared with previously published experimental and simulation result. The CFD results obtained are found to have close matching with experimental result.

4.1 Effect of Ambient Temperature on the performance of gas cooler

Simulations of the CFD model was carried out using ANSYS Fluent 14.0 at two different ambient temperature of 29.4°C and 34°C.

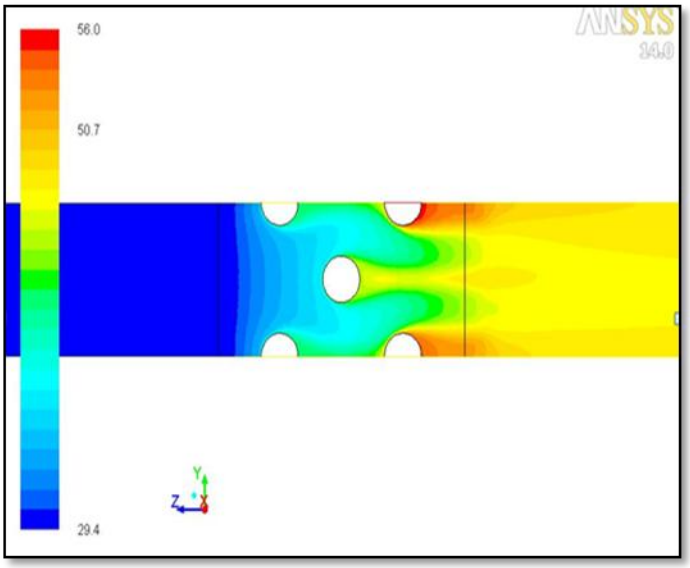


Fig 4: Temperature Contour of air flowing over the tube when ambient air temperature is 29.4° C

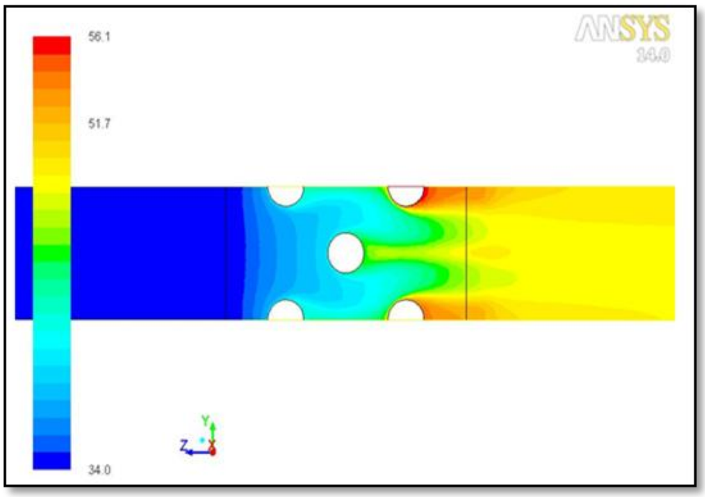


Fig 5: Temperature Contour of air flowing over the tube when ambient air temperature is 34^{o}C

Simulations were performed by keeping ambient atmospheric temperature as 29.4 ^{o}C and 34^{o}C. For both the cases temperature contour followed a similar pattern . But temperature drop per fin was more when atmospheric temperature is 29.4 ^{o}C.

4.2 Performance variations of Gas Cooler with Mass Flow Rate of Carbon dioxide

Simulations of the CFD model was carried out using ANSYS Fluent 14.0 for three cases of carbon dioxide mass flow rate : 0.3 kg/sec, 0.375 kg/sec and 0.5 kg/sec.

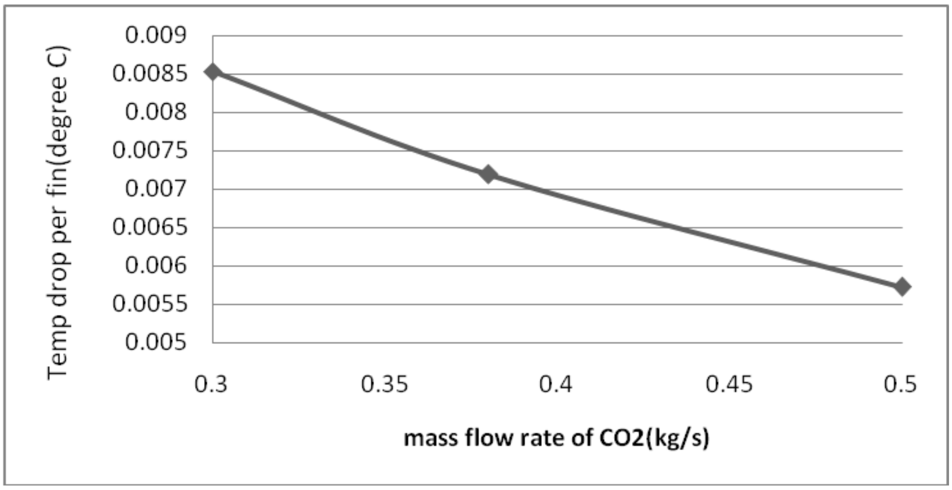


Fig 6 :Temperature drop per fin Vs. mass flow rate of CO_2

CFD simulations were performed by varying mass flow rate of CO_2 and following observations were made from the results.

- Temperature drop per fin decreases with increase in mass flow rate.
- The rate at which temperature drops with mass flow rate is also deceasing with increase in temperature.

4 .3 Performance Variations of Gas Cooler withFin thickness

CFD simulations were carried out in ANSYS FLUENT 14.0 double precision solver for different fin thickness. Changes in temperature drop per fin for various fin thickness is shown in fig 7.

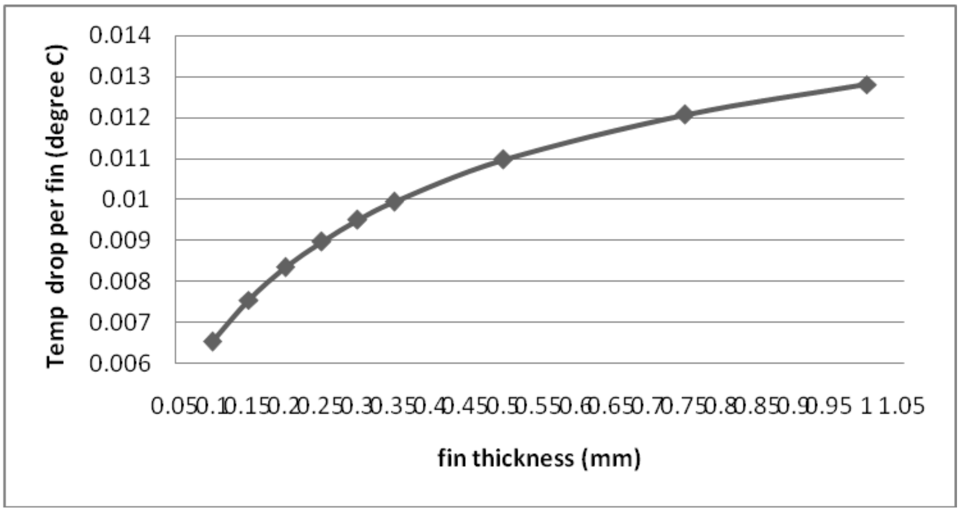


Fig 7:Temperature drop per fib Vs. Fin thickness

Temperature drop per fin is increasing parabolically with fin thickness. Temperature drop per fin is greatly influenced by the fin thickness. There is a large change in the temperature drop when fin thickness changes from 0.05 mm to 0.6 mm after that temperature does not vary much with fin thickness.

5.5 Effect of Tube Thickness

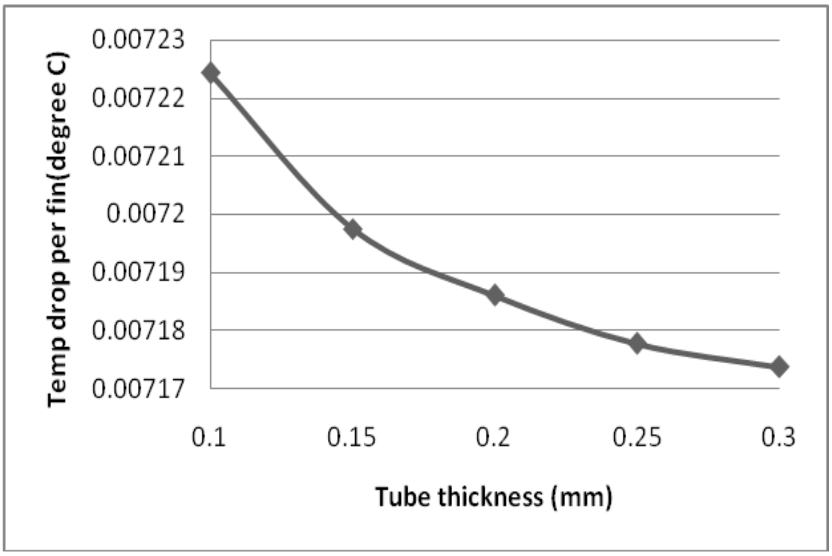


Fig 5.16:Temperature drop per fin Vs. Tube thickness

Temperature drop per fin is decreases parabolically with tube thickness. Temperature drop per fin is not that influenced by the tube thickness. There is no much large change in the temperature drop with the change in tube thickness as compared to fin thickness.

V. CONCLUSION

CFD analysis of a finned tube heat exchanger was successfully carried out. Various techniques were employed while discretizing the geometry to ensure fast and accurate results. The results obtained are validated with the experimental results obtained by Y.T. Ge [10] .

- Temperature drop of CO_2 per fin is found to be decreasing almost linearly with increase in mass flow rate of CO_2. It decreased 15.7 % when mass flow rate increased from 0.3 kg/s to 0.375 kg/s but it was 20% for change in mass flow rate of 0.375 kg/s to 0.5 kg/s.
- Temperature drop per fin is parabolicaly increasing with fin thickness. Temperature drop per fin is greatly influenced by the fin thickness. There is a large change in the temperature drop when fin thickness changes from 0.05 mm to 0.6 mm after that temperature does not vary much with fin thickness.
- Temperature drop per fin is parabolically decreasing with tube thickness. Temperature drop per fin is not that, which is influenced by the tube thickness. There is not much change in the temperature drop with the change in tube thickness as compared to fin thickness.
- Temperature drop per fin is found to be decreasing with mass flow rate of CO_2 and tube thickness whereas it is found to be increasing with air velocity and fin thickness. Temperature drop varies parabolically with tube thickness and fin thickness whereas mass flow rate and air velocity has almost a linear relation with temperature drop.

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