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*Original Article*

# Examination on Properties of Wrinkled Pipes in Helical Coil Heat Exchangers by CFD

S. Nallusamy[1], K. Sujatha[2], R. Balaji[3]

[1]*Department of Adult, Continuing Education and Extension, Jadavpur University, Kolkata, India*
[2]*Department of Chemical Engineering, Dr. M.G.R. Educational and Research Institute, Chennai, India*
[3]*Department of Mechanical Engineering, Dr. M.G.R. Educational and Research Institute, Chennai, India*

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***Abstract*** *- In the current manufacturing scenario, the Helical Coil Heat Exchangers (HCHE) are produced by three roll bending of pipes resulting in the formation of wrinkles on the inner edges of the pipes. The subject of this work is to compare the heat transfer characteristics and fluid flow behaviour in the wrinkled pipe and ideal pipe HCHE. Computational Fluid Dynamics (CFD) analysis for ideal pipe and wrinkled pipe heat exchangers are carried out to investigate heat transfer and fluid flow behaviour. The methodology of CFD is also validated using theoretical analysis. Constant properties and temperature-dependent properties of fluid passing in the heat exchanger are taken for modelling of CFD calculation. The final results revels that, wrinkled pipes have more heat transfer rate and effectiveness than ideal pipes, head loss is increased due to the presence of wrinkles and the rate of mass flow is reduced in wrinkled pipes due to reduction in volume inside the pipe.*

***Keywords*** *- Wrinkling, Bent pipes, HCHE, CFD, Heat transfer characteristics, Fluid flow.*

## 1. Introduction

In general metal pipes are used as fluid ducts and especially heat pipes are produced for heat exchangers and the transport of advanced Nano fluids. While manufacturing bent pipes or curved sections of thin-walled pipes, deformation defects like wrinkling, flattening and ovality of pipes are present [1-4]. The disadvantages of defective bent pipes are the development of micro-cracks which causes the failure of components eventually, it degrades the fluid passing inside the pipes and causes corrosion [5-8].

The ultimate aim of the research is to determine the effects of wrinkles on heat transfer characteristics and fluid flow inside the HCHE. To investigate this, we perform CFD analysis of ideal pipe and wrinkled pipe to determine velocity, Flow rate, turbulence, heat transfer coefficient and effectiveness of heat exchanger [9-11]. To validate CFD results, theoretical calculations of ideal pipe HCHE are compared. Defective pipes are shown in Figure 1.

## 2. Modeling

The HCHE consists of three solid components, one outer pipe of 50.8mm diameter and two inner pipes of 15.875mm diameter. All of them are made up of copper BS6017. Air is passed through the outer pipe and refrigerant-R134a is passed through two inner pipes. The bend diameter of the helical coil is 650mm and the helical pitch is 157.5mm. It is assumed that two inner pipes are kept inside without touching the outer pipe. In the actual case, two inner pipes are twisted over each other to avoid vibration and noise inside the outer pipe and there exists a contact between the outer pipe and inner pipes.

The thickness of the pipes is 1.219mm. The ideal pipe heat exchanger is modelled in Autodesk Inventor Software. The ideal pipe HCHE is shown in the Figure 2. Wrinkled pipe heat exchangers are modelled using Renishaw 3D scanner with Geomagic15 software. Surface data of wrinkles from the actual cut section of the outer pipe is scanned and patched randomly to the helical coil with a total number of wrinkles to be 15 and an average wrinkling depth to be 15mm. The wrinkled pipe HCHE is shown in Figure 3.

**Fig. 1 HCHE wrinkled pipes**

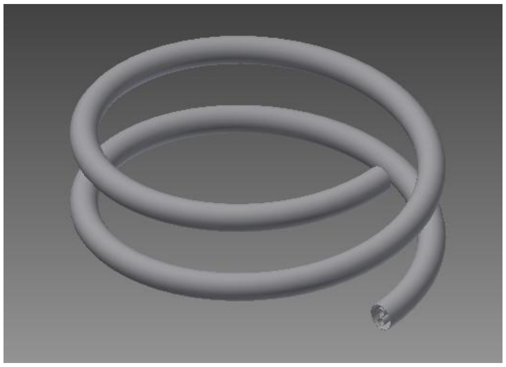

**Fig. 2 Ideal pipe helical coil heat exchanger model**

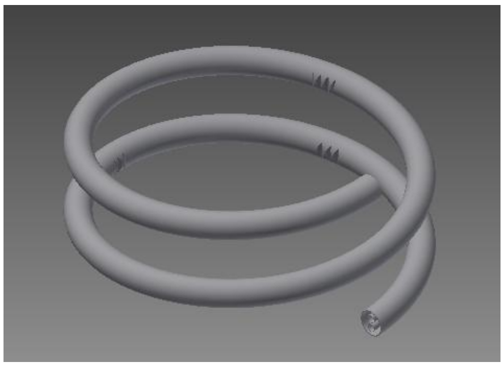

**Fig. 3 Wrinkled pipe HCHE model**

## 3. HCHE CFD Study

The heat exchanger used in commercial air dryers is taken for analysis where the refrigerant used is R134a. The problem is solved in two cases. In the first case, properties are taken as constant at ambient temperature.

In the second case, temperature-dependent properties are taken by fitting a curve using regression analysis in Math CAD software from data points collected [12-14]. The fluid properties at a constant temperature are listed in Table 1.

Below are the temperature-dependent properties equations of R134a:

μ (T) = -1E-05T2 + 0.046T - 0.748; 10^-6 $PaS$

ρ (T) = 1E-08T5 - 2E-05T4 + 0.014T3 - 4.823T2 + 781.8T – 50618; $kg/m3$

K (T) = -5E-10T4 + 6E-07T3 - 0.000T2 + 0.066T - 5.407; $W/mK$

Cp (T) = -2E-11T6 + 5E-08T5 - 4E-05T4 + 0.015T3 - 3.816T2 + 489.6T – 26148; $Kj/kgK$

Temperature values are in Kelvin. Equations are valid from the range of $27^0$K to $37^0$ K.

CFD analysis is carried out in ANSYS-FLUENT software. Solid and fluid domains are modelled in cell zone conditions. Inlets and outlets of air and R134a are selected.

**Table 1. Fluid properties at a constant temperature**

| Fluid Properties | Air-10 $bar$,23°$c$ | R134a-6$bar$,10°$c$ |
|---|---|---|
| Isobaric Specific heat, Cp ($kJkgK$ ) | 1.02232 | 1.3247 |
| Density, ρ ($kg/m2$) | 11.7988 | 1314.1407 |
| Dynamic viscosity, μ ($kgm/s$) | 1.84916e-5 | 4389.64e-6 |
| Thermal Conductivity, K ($Wm/K$) | 0.0242 | 0.095625 |

**Table 2. Mesh details of ideal pipe heat exchanger**

| Domain | Nodes | Elements |
|---|---|---|
| Air | 358656 | 1767588 |
| Outer Pipe | 187118 | 862064 |
| Ref1 | 112336 | 94107 |
| Ref2 | 87658 | 396390 |
| Refpipe1 | 77033 | 44226 |
| Refpipe2 | 78720 | 47531 |
| All Domains | 901521 | 3211906 |

**Table 3. Boundary conditions**

| Boundary Conditions | Air inlet | R134a inlet1,inlet2 |
|---|---|---|
| Temperature, $K$ | 296 | 283 |
| Pressure, $bar$ | 10 | 2.7 |
| Velocity, $m/s$ | 86.81 | 99.81 |

The analysis type is pressure based. The velocity formulation is absolute and time is a steady state. Gravity is defined as y = -9.81 $m/s^2$. The model is meshed using tetrahedral elements. Mesh details for the ideal pipe heat exchanger are shown in Table 2. Boundary conditions for the problem are shown in Table 3. Convection interfaces between air, inner pipe and refrigerant are defined. They are shown in Figure 4.

Solver used for CFD analysis is the k-ε model (2 equations) with standard wall functions. The energy equation is set to ON. Temperature variation for ideal and wrinkled is shown in Figure 5 and Figure 7.

Sliced view of the air domain at different angles of 180°, 360°and 540° are shown in Figure 6 and Figure 8 Pressure variation and turbulence intensity are calculated in the analysis for ideal and wrinkled it is shown in Table 4.

**Table 4. Pressure drop and turbulence intensity of heat exchanger**

| Fluid Characteristics | Ideal Pipe | Wrinkled Pipe |
|---|---|---|
| Pressure drop, Δp ($kpa$) | 130.685 | 307.6 |
| Max. Turbulence Kinetic energy, TKE ($j/kg$) | 44.54 | 1024.3 |

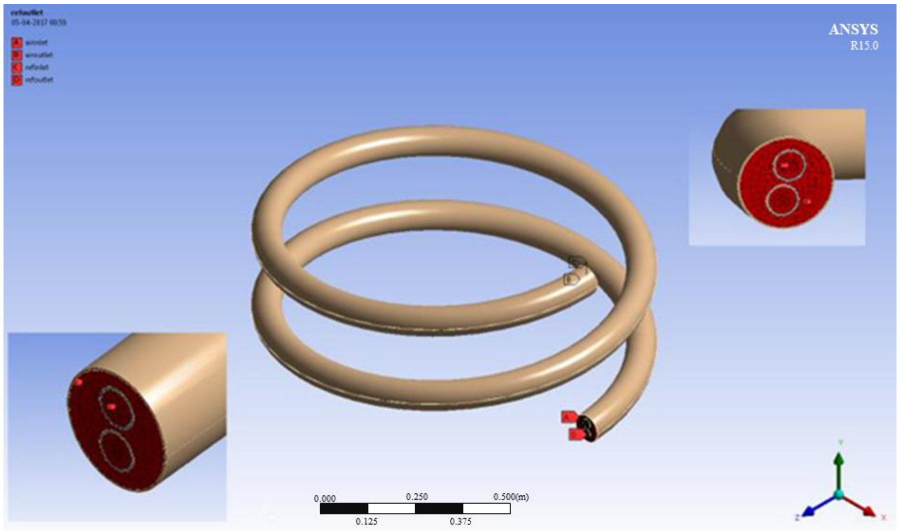


**Fig. 4 Boundary regions of the HCHE model**

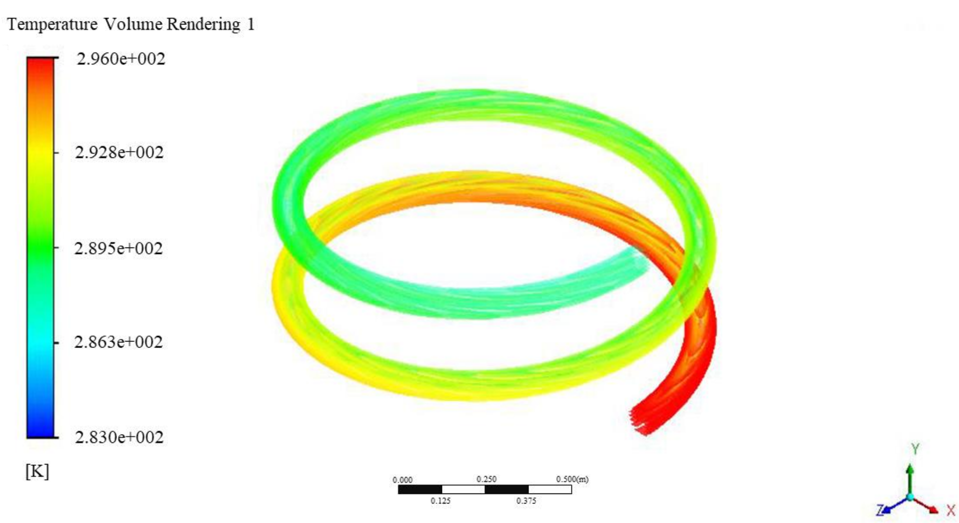


**Fig. 5 Temperature variation in ideal pipe HCHE**

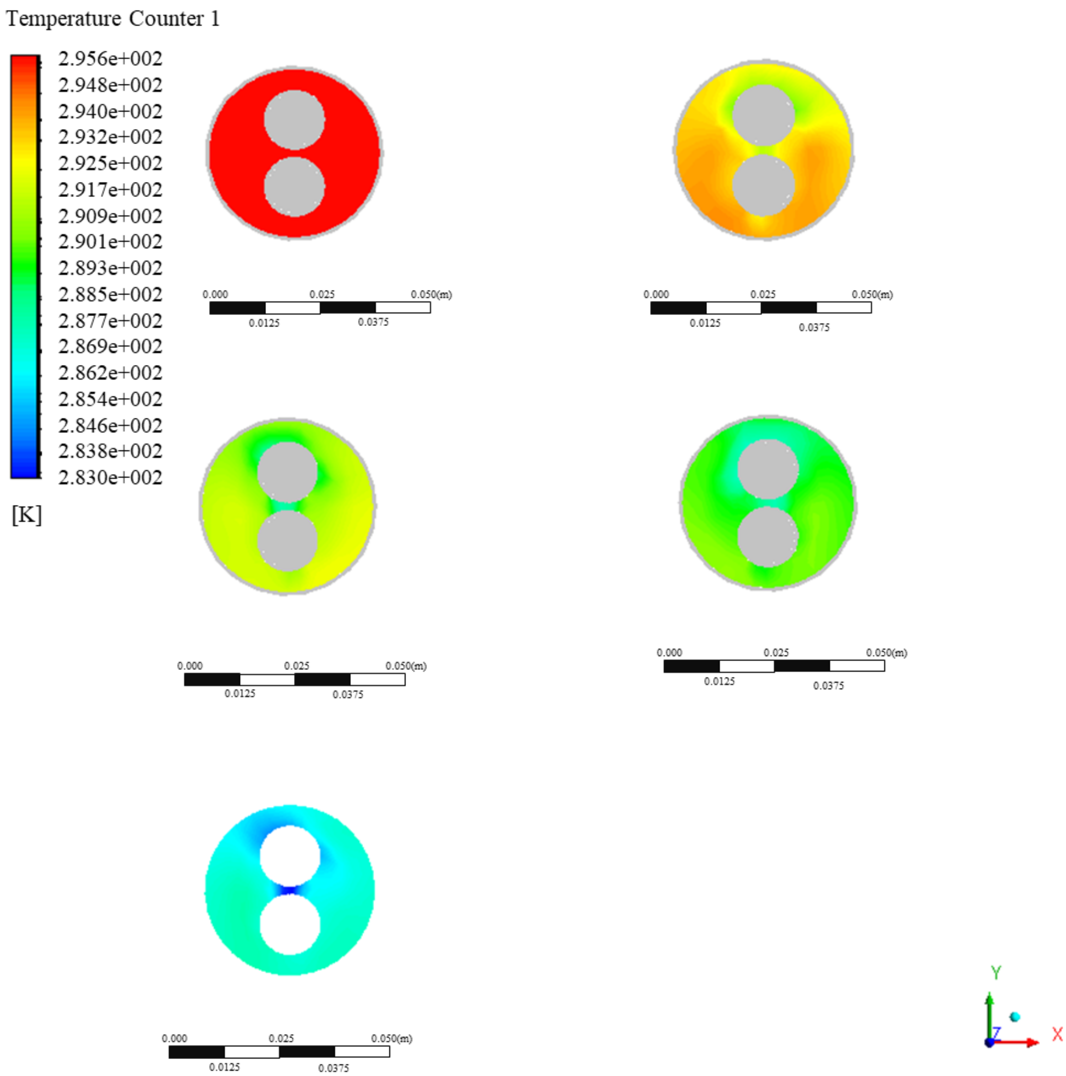


**Fig. 6 Sliced view of temperature distribution in ideal pipe HCHE at the inlet, 180°, 360º, 540° and outlet**

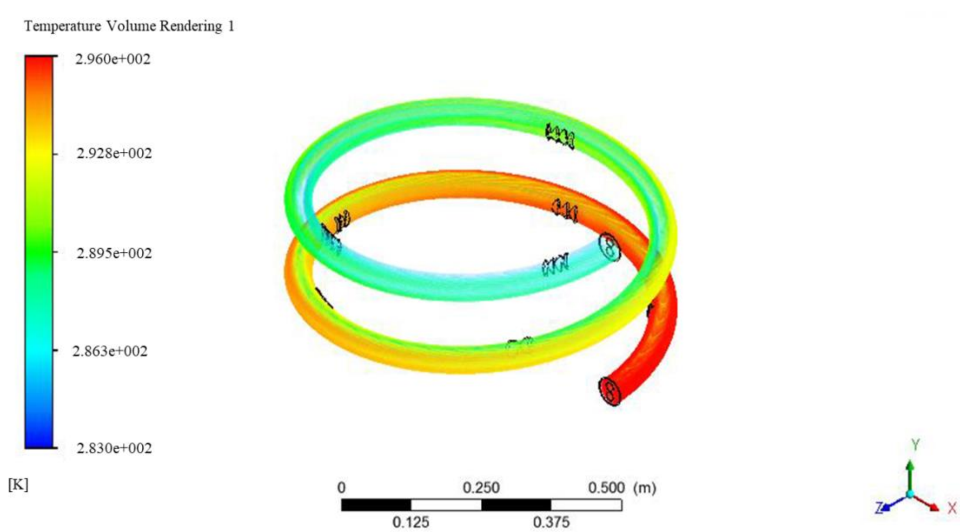


**Fig. 7 Temperature variation in wrinkled pipe HCHE**

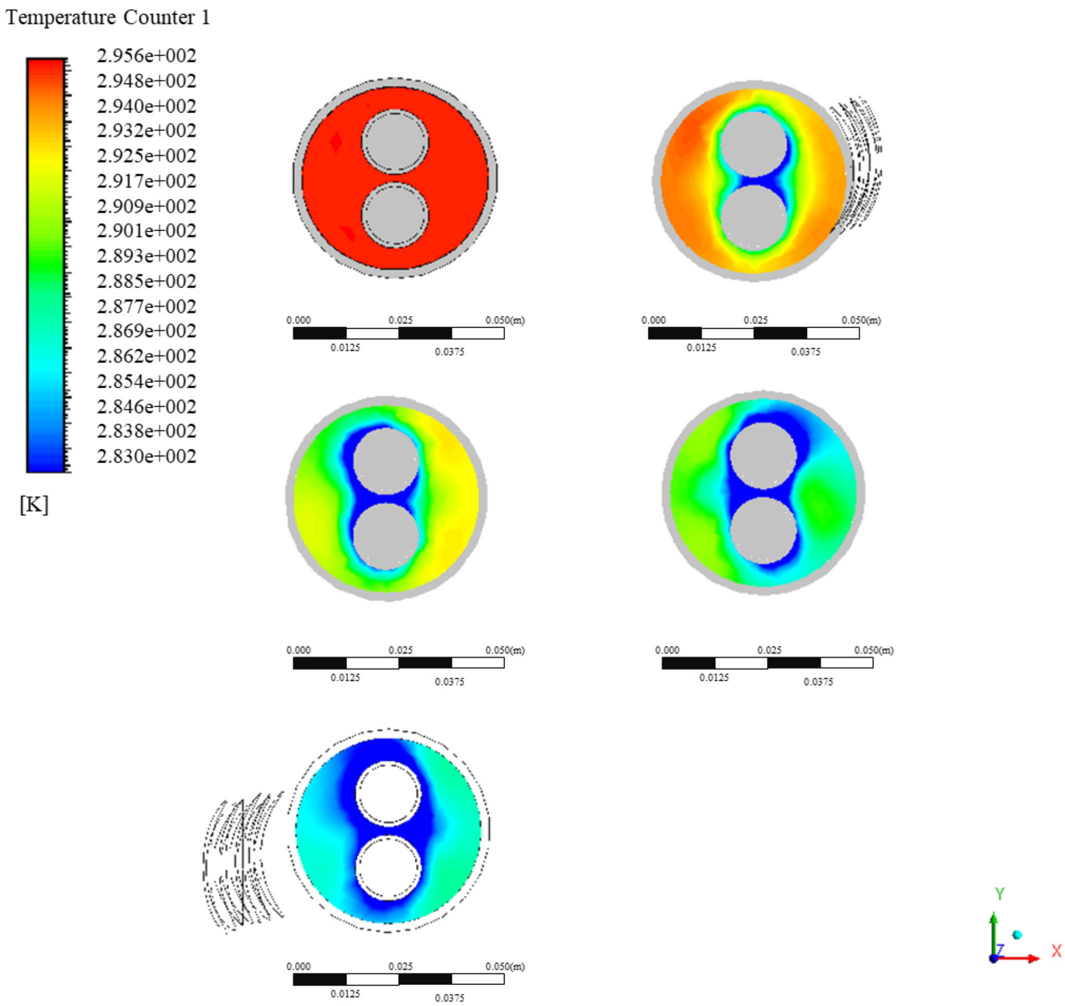


**Fig. 8 Sliced view of temperature distribution in wrinkled pipe HCHE at the inlet, 180°, 360°, 540° and outlet**

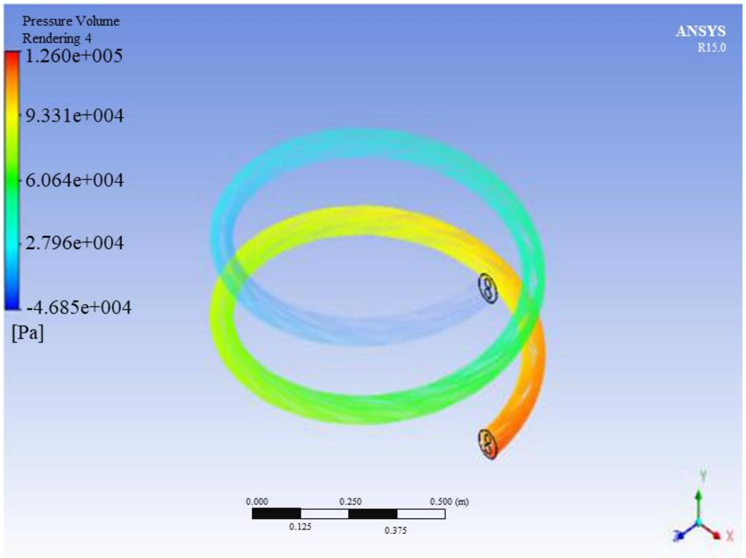


**Fig. 9 Pressure variation in ideal pipe HCHE**

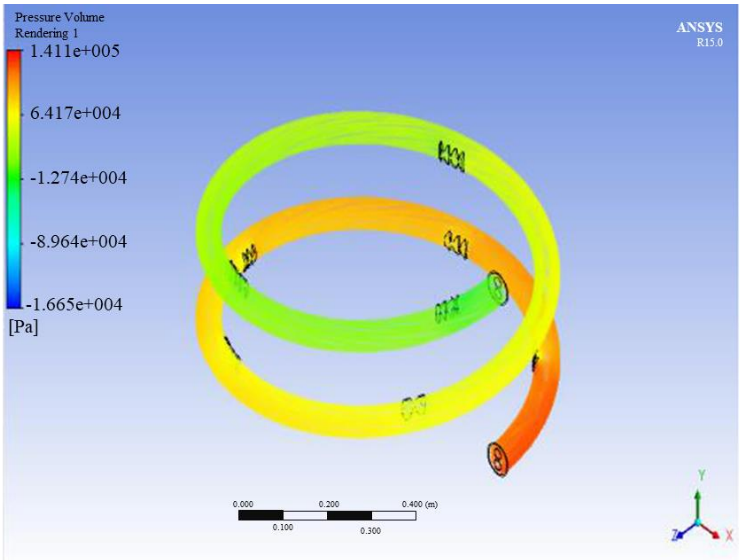


**Fig. 10 Pressure variation in wrinkled pipe HCHE**

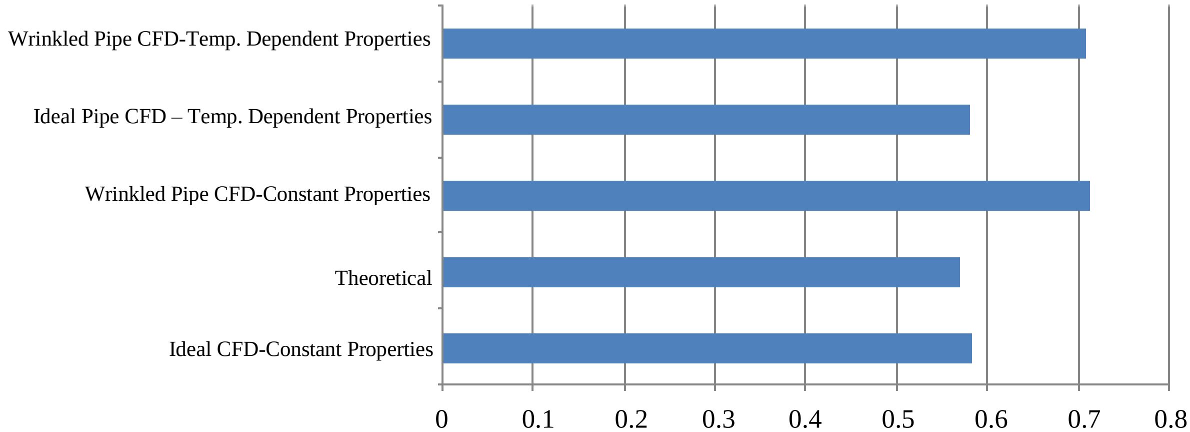


**Fig. 11 Comparison of the effectiveness of HCHE**

## 4. Theoretical Analysis of Ideal Pipe HCHE

The design of the double pipe heat exchanger is taken for heat transfer analysis with basic correlations [15-17]. Calculations are shown below. Nusselt number correlation is taken from [18-20].

The volume flow rate of air, $V_{air} = 509.7032\ m^3/hr$
Air annular C.S area, $A_{air}= 0.00163\ m2$
Mean Velocity of air, u = V/A = 86.81 $m/s$
The mass flow rate of air, M = ρAu = 1.6705 $kg/s$
Reynolds number of air, Re = ρUdh/μ =2.11036×106
Dean number of air, De = Re(√(dh/D)) = 510.936×103
Nusselt number, $N_u = 0.7Re^{0.43}Pr^{1/6}(d/D)^{0.07} = 179.88$
Volume flow rate of R134a, Vref = 2.7 $m3/hr$
Refrigerant C.S area, Aref = 0.000197 $m2$
Mean Velocity of R134a, uref = V/A = 99.81 $m/s$
Mass flow rate of R134a, Mref = ρAu = 0.96 $kg/s$
Reynolds number of R134a, Reref = ρUdh/μ = $1.7652\times10^4$
Dean number, Deref = 2742.059

Nusselt Number, $N_u= 0.7Re^{0.43}Pr^{1/6}(d/D)^{0.07} = 292$
Heat Capacity rates
C air = Cpair.Mair = 1707.785 $W/K$
C ref = 2*Cpref.Mref = 2544.33$kW/K$
Cr = Cmin/Cmax = 0.6712
Heat transfer Coefficients
Inner wall coefficient, hc1 = (k.Nu)/Di = 114.254 $W/m^2k$
Outer wall coefficient, hc2 = (k.Nu)/Do = 1758.897$W/m^2k$
Overall coefficient, $U= (1/h_{c1} + L/k + 1/h_{c2})^{-1}$=1623.8 $W/m^2k$
Heat transfer Area, AT = 2$\pi$L (Di + Do) = 1.15$m^2$
NTU = UA/Cmin = 1.093
Effectiveness

$$\varepsilon = \frac{1 - \exp\left[-\mathrm{NTU}(1 - \mathrm{C_r})\right]}{1 - \mathrm{C_r}\exp\left[-\mathrm{NTU}(1 - \mathrm{C_r})\right]} = 0.5679$$

Total heat transfer rate Q= έ. $C_{min}$. (Thi - Tci) = 12.608$kW$
Cold fluid Outlet temperature
Tco = Tci + (q/Cmax) = 287.93$K$
Hot fluid Outlet temperature
Tho = Thi - (q/Cmin) = 288.6$K$

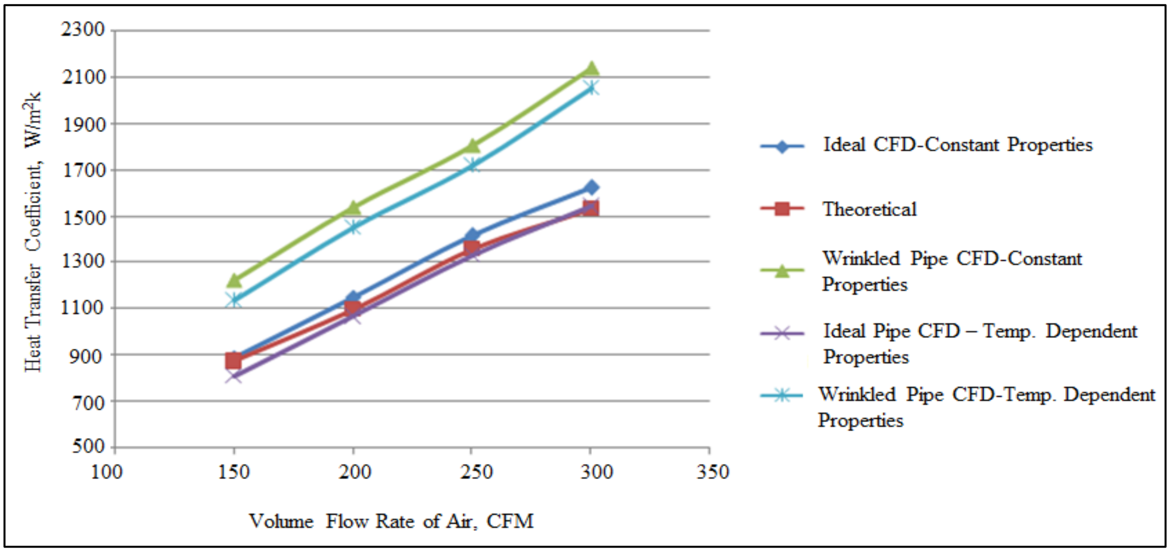


**Fig. 12 Comparison of heat transfer coefficient of HCHE**

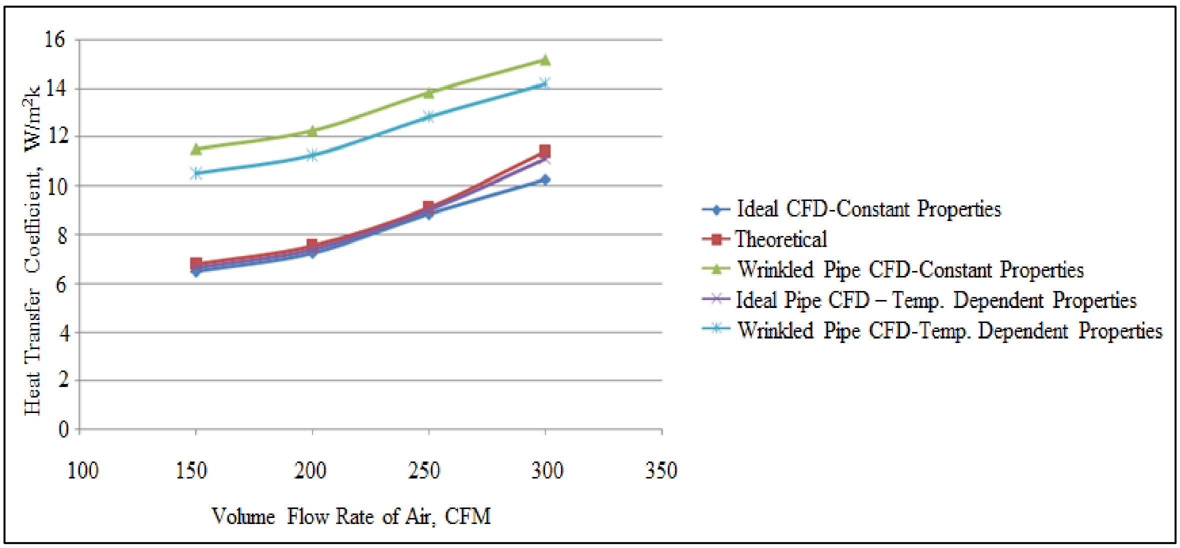


**Fig. 13 Comparative results of the heat transfer rate of HCHE**

## 5. Results and Discussions

Comparison between ideal and wrinkled HCHE in heat transfer behaviour and fluid flow characteristics are discussed in this section. So far analysis is carried out for 300cfm of air. A similar analysis is carried out for different volume flow rates of air for 150, 200 and 250 cfm.

The results for the respective are shown below. The outlet of the air domain is sliced to view the results of mass flow rate and temperature. It is shown in Table 5. Variation of the heat transfer coefficient is shown in Figure 12. The variation of the heat transfer rate is shown in Figure 13. Effective of heat exchangers is compared in Figure 11.

**Table 5. Air outlet condition of heat exchangers**

| Air Domain | Ideal Pipe | Wrinkled Pipe |
|---|---|---|
| Volume flow rate, $m^3/s$ | 0.1422 | 0.1392 |
| Mass flow rate, $kg/s$ | 1.5329 | 1.4995 |
| Temperature, $K$ | 288.42 | 286.74 |

## 6. Conclusion

The numerical investigation on the effects of HCHE with CFD was carried out and conclusions arrived from the work done are listed below.

- Wrinkled pipes increase the turbulence of fluid inside and hence the heat transfer coefficient is improved.

- Wrinkled pipes have more heat transfer rate and effectiveness than ideal pipes.
- Pressure drop, i.e. head loss is increased due to the presence of wrinkles.
- Mass flow rate is reduced in wrinkled pipes due to a reduction in volume inside the pipe.
- Fluid flow is fully developed on the outer edges of the helical coil pipe due to the centrifugal effect.
- Consideration of temperature-dependent properties for fluid flow is more approximate than constant properties.

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