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"Analysis Of Thermoflow Characteristics Of Offset Strip Fins With Different Working Fluids"

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Abstract

The paper emphasizes on the analysis of thermo flow characteristics for the offset strip fin. This is the most widely used fin geometry in high performance plate fin heat exchangers. The correlations suggested in this work by the researcher for the j values in the turbulent and transition regions estimated the values of j which are close to the values suggested by Manglik and Bergles. The correlations for j and f values are presented. The modified correlations which can be applied for working fluid other than air are also presented. The correlations presented are based on Prandtl number. The working fluids used for analysis are air, mercury, noble gas and R-12.The graphical results are incorporated in the work for different blockage ratio up to 35%. The effect on colburn factor for different fluids with respect to Reynolds number is analyzed in the work. The probable cause for variation in the Colburn factor, j with change in working fluid is also investigated. And as the Colburn factor bears a directly proportional relationship to the convective heat transfer coefficient and also bears a an inversely proportional relationship to the product of thermal conductivity and density, these parameters being different for different fluids cause a change in the heat transfer characteristics of the fluids. The results obtained experimentally are found in agreement to the effect of the various parameters. Further future scope is also manifested at the end of the work.

LIST OF NOMENCLATURE

A Area (m^2)

c_p Specific heat at constant pressure (J/kg-K)

D_h Hydraulic dia. (mm)

f Friction factor, $\frac{2\Delta p}{\rho u_c^2}\left(\frac{D_h}{4L}\right)$

h Height of offset strip fin (mm)/heat transfer coefficient (W/m^2-K)

j Colburn factor, $\frac{Nu}{\rho u_c^2}\left(\frac{D_h}{4L}\right)$

JF JF factor, $[(j/j_{ref}) / (f/f_{ref})]^{1/3}$

k Thermal conductivity (W/m-K)/ turbulent Kinetic energy (m^2/s^2)

l Length of the offset strip fin(mm)

$\dot{m}$ mass flow rate (kg/s)

Nu Nusselt no., $\frac{\bar{h} D_h}{k}$

n Normal direction

Pr Prandtl no., $\frac{\mu c_p}{k}$

p Pressure (Pa)

Δp Pressure drop (Pa)

$\dot{Q}$ Heat transfer rate (W)

Re Reynolds number $\frac{\rho u_c D_h}{\mu}$

S_Φ Source term of Φ

s Spacing of the offset strip fin (mm)

T Temperature ($°C$)

t Thickness of the offset strip fin (mm)

u,v,w Velocity (m/s)

Greek symbols

α s/h

β Blockage ratio

γ t/s

δ t/l

Γ_ϕ Diffusivity variable

δ_{ij} Kronecker delta

ε Dissipation rate of turbulent kinetic energy (m^2/s^3)

ρ density(kg/m^3)

ϕ general dependent variable

µ Dynamic viscosity (kg/ms)

ω specification dissipation rate (s^{-1})

Subscripts

eff effective

in inlet

opt optimum

out outlet

ref reference

t turbulence

total total

vac vacancy

wall wall

1. Introduction

Extended surfaces have wide industrial application as fins attached to the walls of heat transfer equipments in order to increase the rate of heat transfer i.e. heating or cooling. Fins are of many shapes & forms. In the study of heat transfer, a fin is a surface that extends from an object to increase the rate of heat transfer to or from the environment by increasing convection. The amount of conduction, convection, or radiation of an object determines the amount of heat it transfers. Increasing the temperature difference between the object and the environment, increasing the convection heat transfer coefficient or increasing the surface area of the object increases the heat transfer. Sometimes, it is not economical or it is not feasible to change the first two options. Adding a fin to an object, however, increases the surface area and can sometimes be an economical solution to the heat transfer problems.

Offset-strip fins are widely used for plate-fin heat exchangers to enhance heat transfer rate by enlarging surface area and regenerating thermal boundary layer in each column. However, offset-strip fins induce a large pressure drop between the inlet and outlet of a plate-fin heat exchanger. Therefore, the heat transfer and pressure drop in offset-strip fins need to be investigated. Furthermore, the offset-strip fin must be optimally designed so that it can reconcile these contradictory phenomena. Offset-strip fin heat exchangers have been in use for decades. This type of compact heat exchanger takes advantage of boundary layer restarting to enhance heat transfer over that of plain-fin heat exchangers. Since the average boundary-layer thickness decreases significantly when offset-strip fins are used, the convection coefficient increases. At moderate Reynolds numbers ($Re > 700$), vortex shedding can occur in the array, causing further heat transfer enhancement. Both of these enhancement mechanisms also increase pressure drop across the array. Heat transfer is typically proportional to the flow velocity, but the power required to move the flow (pumping power, or fan power) is proportional to the velocity cubed;

therefore, offset-strip fin heat exchangers are usually operated at Reynolds numbers much below 1,000 in order to manage heat-duty-pumping-power design tradeoffs.

At these low Reynolds numbers, the air-side flow is steady and laminar. The thermal-hydraulic performance of offset-set strip fin heat exchangers has been studied extensively for flows in this regime.

2. Literature review

Researchers have studied about offset strip fins [1–10]. Largely these studies involved air as the working fluid, few fin geometries are applicable to practical offset-strip fins with working fluids other than air. Kays and London [1] were the first to explore a correlation for offset-strip fins based on experimental results. Manson [2] performed experiments with fin geometries. Wieting [3] obtained a correlation using 22 fin geometries. Mochizuki et al. [4] presented more accurate correlations by modifying those of Wieting [3]. Joshi and Webb [5] suggested correlations in both laminar and turbulent regimes. Manglik and Bergles [6] presented a correlation that could be applied to the laminar, transition, and turbulent regimes by using experimental data from the literature. Because the working fluid was air, however, their correlations cannot be used for other working fluids whose Prandtl numbers are higher than that of air. For this reason, some studies [7–10] have considered working fluids other than air. For instance, Tinaut et al. [7] experimented with offset strip fin heat exchangers that used water and engine oil. Hu and Herold [8] investigated heat transfer and pressure drop in offset strip fins with water and polyalphaolefin as the working fluids. Muzychka [9] and Muzychka and Yovanovich [10] performed experiments using transmission oil as the working fluid and derived correlations by an analytical model. The number of fin geometries they tested, however, was not sufficiently large to establish a general correlation. The optimal design of a thermal fluid system, such as an offset strip fin heat exchanger, generally uses a function-based approximation method instead of a gradient-based approximation method [11] because of the latter's excessive computational time and the nonlinearity of the function [12]. The response surface method [13–16] utilizes a function-based approximation and is a global optimization method applicable to many design fields. The response surface method accurately describes the trend of the design solution. However, this method cannot accurately present the local value when the variation of the objective function according to the design variables is very large. M.S Kim, Jonghyeok Lee, Se-Jin Yook, Kwan-Soo Lee presented correlations based on prandtl number for blockage ratio up to 35%.

3. Theoretical analysis

3.1 Governing equations

In the present model, it is assumed that:
(1) The flow is three-dimensional and incompressible.
(2) The working fluids are in a single phase, and their properties remain constant.
(3) Natural convection and thermal radiation can be neglected.
Depending on the Reynolds number, the flow across an offset strip fin is categorized as laminar, transition, or turbulent. Since oscillatory flow exists in the transition and turbulent regimes.

The governing equation is as follows:

$$\frac{\partial}{\partial t}(\rho\emptyset)+\frac{\partial}{\partial x_i}(\rho u_i\emptyset)=\frac{\partial}{\partial x_i}\left(\Gamma_\emptyset\frac{\partial\emptyset}{\partial x_i}\right)+S_\emptyset. \qquad (1)$$

Interfacial boundary conditions

At the interface between the fluid and solid, the boundary conditions were:

$$u_{wall}=v_{wall}=w_{wall}=0, and\ T=T_S. \qquad (2)$$

Inlet and outlet conditions

The inlet and outlet conditions were described by:

$$\dot{m}=\dot{m}_{in},\quad T_f=T_{in},\quad I_{in}=0.16Re_{D_h}^{-\frac{1}{8}}, \qquad (3)$$

$$\dot{m}=\dot{m}_{out}=\dot{m}_{in},\quad \frac{\partial k}{\partial n}=0,\quad \frac{\partial\omega}{\partial n}=0,\quad \frac{\partial\rho}{\partial n}=0,\quad \frac{\partial T}{\partial n}=0. \qquad (4)$$

Following Manglik and Bergles [6], the **hydraulic diameter** was defined as:

$$D_h=\frac{4shl}{2(sl+hl+th)+ts}. \qquad (5)$$

The blockage ratio is defined as:

$$\beta=\frac{A_{total}-A_{vac}}{A_{total}}=\frac{(2s+2t)(h+t)-2sh}{(2s+2t)(h+t)}, \qquad (6)$$

$$=\left(1-\frac{1}{1+\alpha\gamma+\gamma+\alpha\gamma^2}\right)\times 100\%. \qquad (7)$$

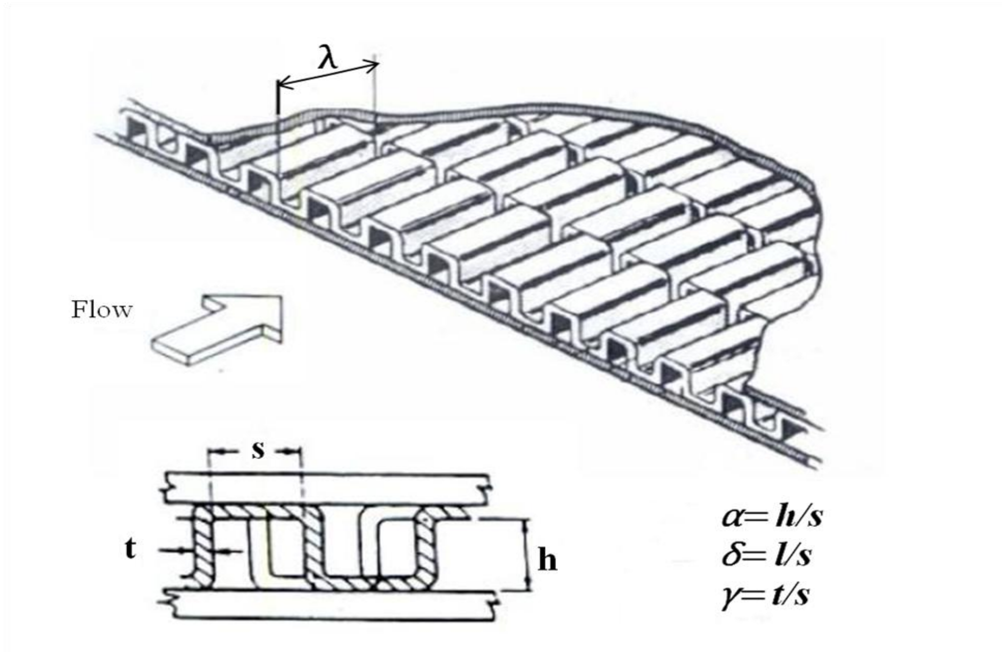

***Fig. 1:** Geometry of the offset strip fin*

Where,

l= strip length of the offset strip fin (mm)

t= thickness of the offset strip fin (mm)

h= height of the offset strip fin (mm)

s= spacing of the offset strip fin (mm)

Correlations for air are:[17]

- $\beta < 20\%$:

$$f = \exp(7.91)\,(\alpha)^{-0.159}(\delta)^{0.358}(\gamma)^{-0.033}\left(Re_{D_h}\right)^{\left(0.126\ln Re_{D_h}-2.3\right)}, \quad (8)$$

$$j_{air} = 0.655(\alpha)^{-0.136}(\delta)^{0.236}(\gamma)^{-0.158}\left(Re_{D_h}\right)^{\left(0.015\ln Re_{D_h}-0.623\right)}. \quad (9)$$

- $20\% \leq \beta < 25\%$:

$$f = \exp(9.36)\,(\alpha)^{-0.0025}(\delta)^{-0.0373}(\gamma)^{1.85}\left(Re_{D_h}\right)^{\left(0.142\ln Re_{D_h}-2.39\right)}, \quad (10)$$

$$j_{air} = 1.18(\alpha)^{-0.134}(\delta)^{0.0373}(\gamma)^{0.118}\left(Re_{D_h}\right)^{\left(0.0445\ln Re_{D_h}-0.982\right)}. \quad (11)$$

- $25\% \leq \beta < 30\%$:

$$f = \exp(5.58)\,(\alpha)^{-0.36}(\delta)^{0.552}(\gamma)^{-0.521}\left(Re_{D_h}\right)^{\left(0.111 \ln Re_{D_h} - 1.87\right)}, \quad (12)$$

$$j_{air} = 0.49(\alpha)^{-0.23}(\delta)^{0.245}(\gamma)^{-0.733}\left(Re_{D_h}\right)^{\left(0.049 \ln Re_{D_h} - 0.971\right)}. \quad (13)$$

- $30\% \leq \beta < 35\%$:

$$f = \exp(4.84)\,(\alpha)^{-0.48}(\delta)^{0.347}(\gamma)^{0.511}\left(Re_{D_h}\right)^{\left(0.089 \ln Re_{D_h} - 1.49\right)}, \quad (14)$$

$$j_{air} = 0.22(\alpha)^{-0.315}(\delta)^{0.235}(\gamma)^{-0.727}\left(Re_{D_h}\right)^{\left(0.0313 \ln Re_{D_h} - 0.729\right)}. \quad (15)$$

Correlations of offset-strip fins according to Prandtl number [17]

New j correlations with a coefficient of determination (R^2) of 0.95 are suggested as follows, as functions of the Prandtl number:

- $\beta < 20\%$:

$$j_{Pr} = \exp(1.96)\,(\alpha)^{-0.098}(\delta)^{0.235}(\gamma)^{-0.154}\left(Re_{D_h}\right)^{(0.0634\, lnRe - 1.3)}(Pr)^{0.00348}. \quad (16)$$

- $20\% \leq \beta < 25\%$:

$$j_{Pr} = 1.06(\alpha)^{-0.1}(\delta)^{0.131}(\gamma)^{-0.08}\left(Re_{D_h}\right)^{(0.0323\, lnRe - 0.856)}(Pr)^{0.0532}. \quad (17)$$

- $25\% \leq \beta < 30\%$:

$$j_{Pr} = \exp(1.3)\,(\alpha)^{0.004}(\delta)^{0.251}(\gamma)^{0.031}\left(Re_{D_h}\right)^{(0.0507\, lnRe - 1.07)}(Pr)^{0.051}.$$

4. RESULTS & DISCUSSION

The graphical results are obtained for number of fins 6, 18 & 22. [17]

For β < 20%.

The graphical results obtained for the analysis of j factor with working fluid air, mercury, noble gas and R-12.

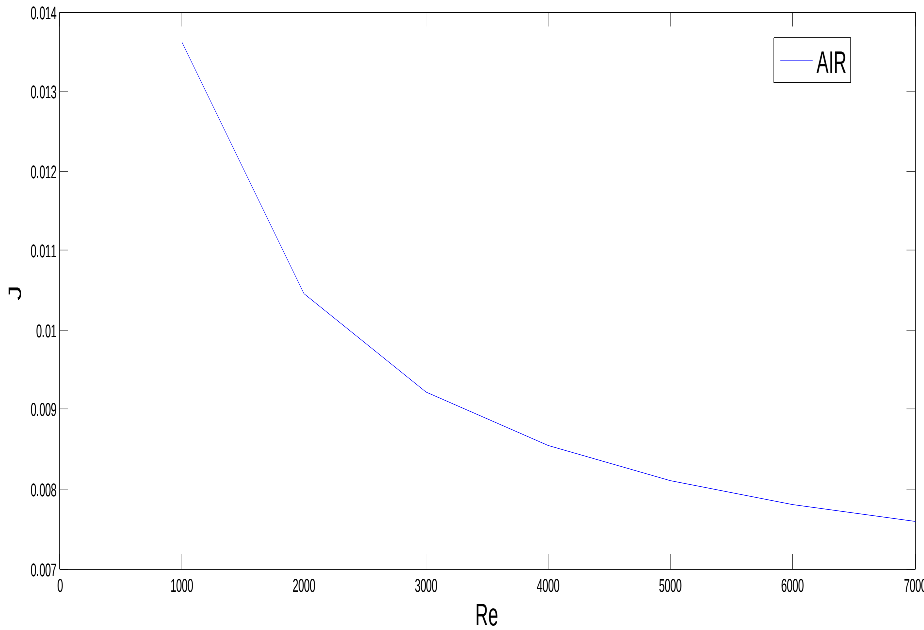

Fig.4.1: *Representation of j values as a function of the Prandtl number with working fluid air vs. Re on the basis of hydraulic diameter for offset-strip fin #6.*

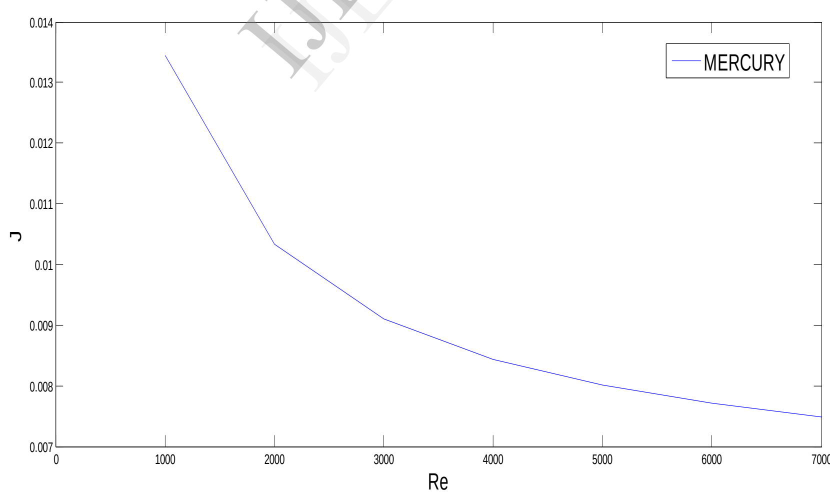

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Fig.4.2: *Representation of j values as a function of the Prandtl number with working fluid mercury vs. Re on the basis of hydraulic diameter for offset-strip fin #6.*

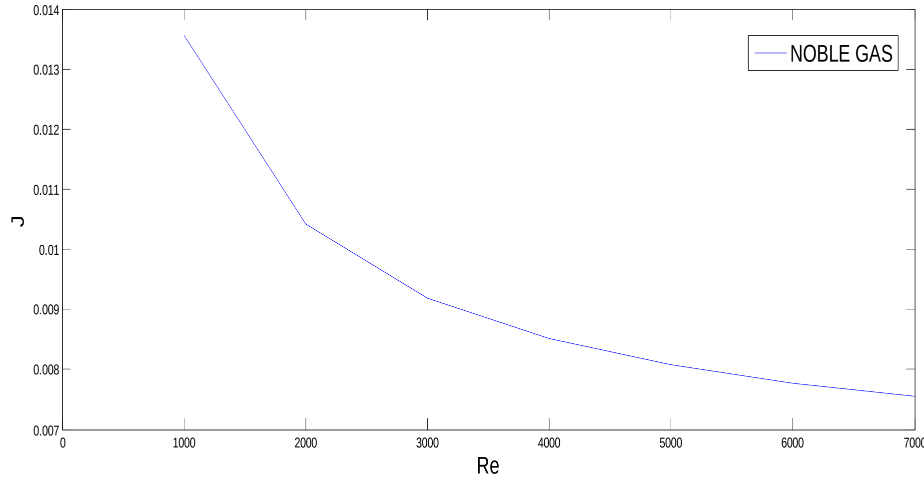

Fig.4.3 *Representation of j values as a function of the Prandtl number with working fluid noble gas vs. Re on the basis of hydraulic diameter for offset-strip fin #6.*

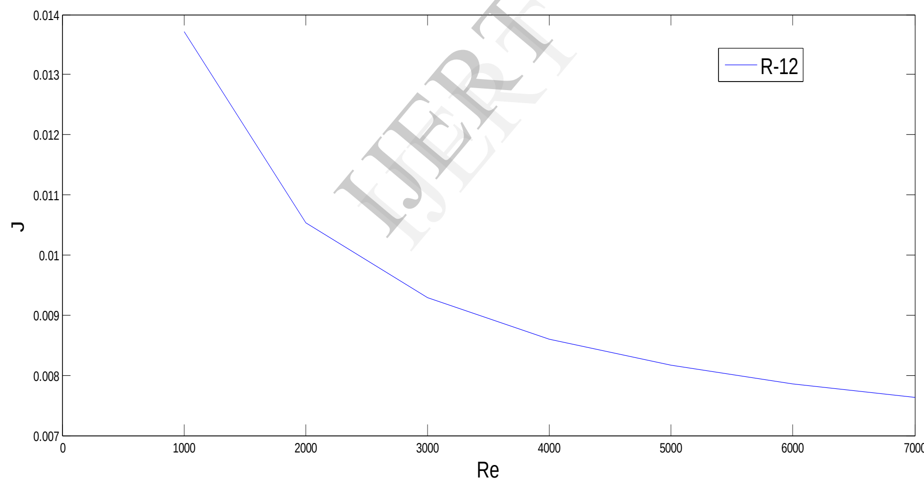

Fig.4.4: *Representation of j values as a function of the Prandtl number with working fluid R-12 vs. Re on the basis of hydraulic diameter for offset-strip fin #6.*

For 20% < β < 25%.

The graphical results obtained for the analysis of j factor with working fluid air, mercury, noble gas and R-12.

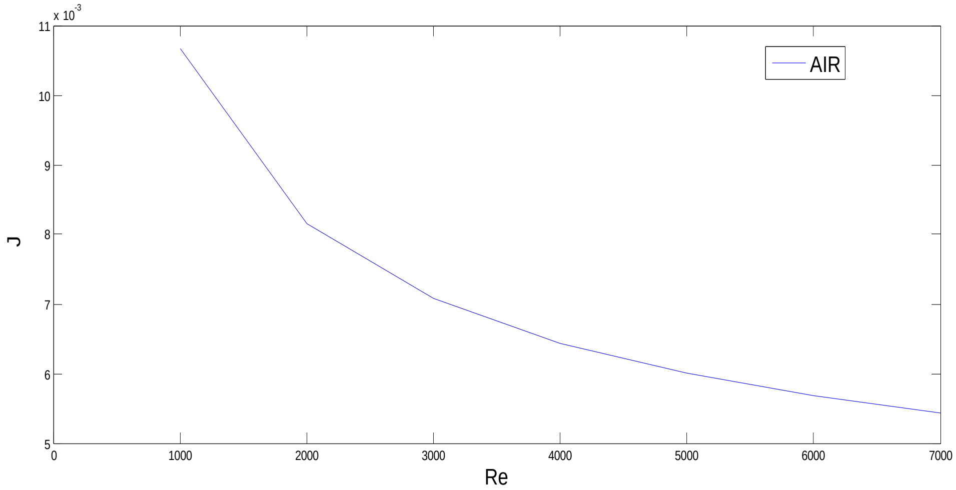

Fig.4.5: *Representation of j values as a function of the Prandtl number with working fluid air vs. Re on the basis of hydraulic diameter for offset-strip fin #18.*

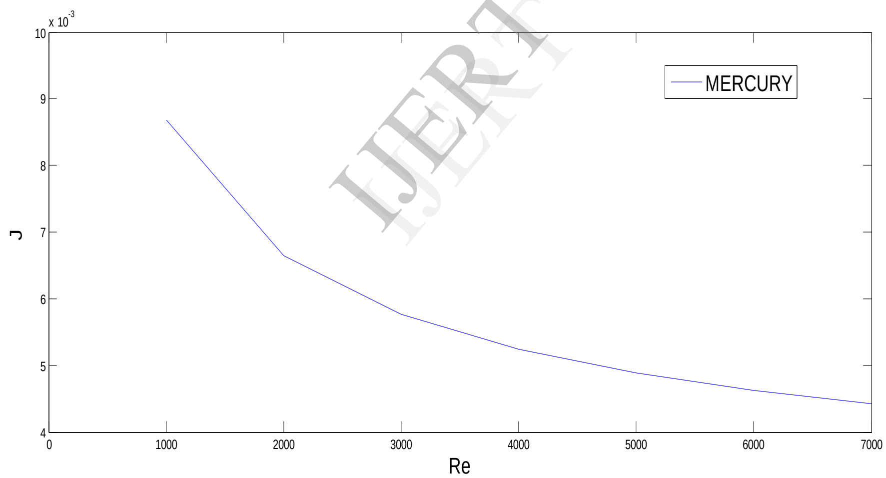

Fig 4.6: *Representation of j values as a function of the Prandtl number with working fluid mercury vs. Re on the basis of hydraulic diameter for offset-strip fin #18.*

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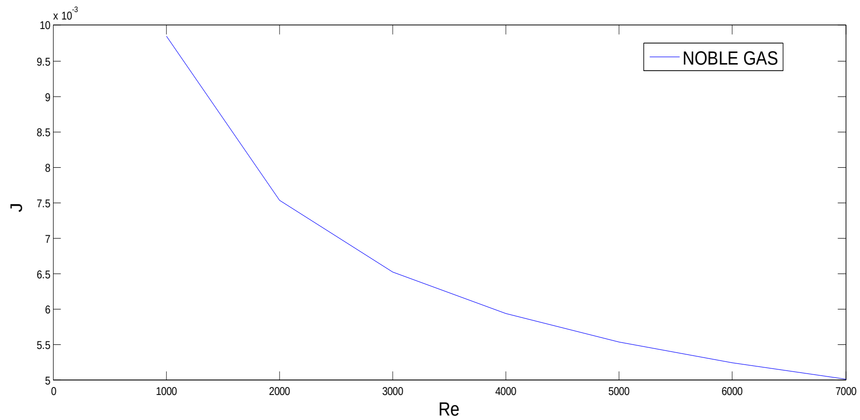

Fig.4.7: Representation of j values as a function of the Prandtl number with working fluid noble gas vs. Re on the basis of hydraulic diameter for offset-strip fin #18.

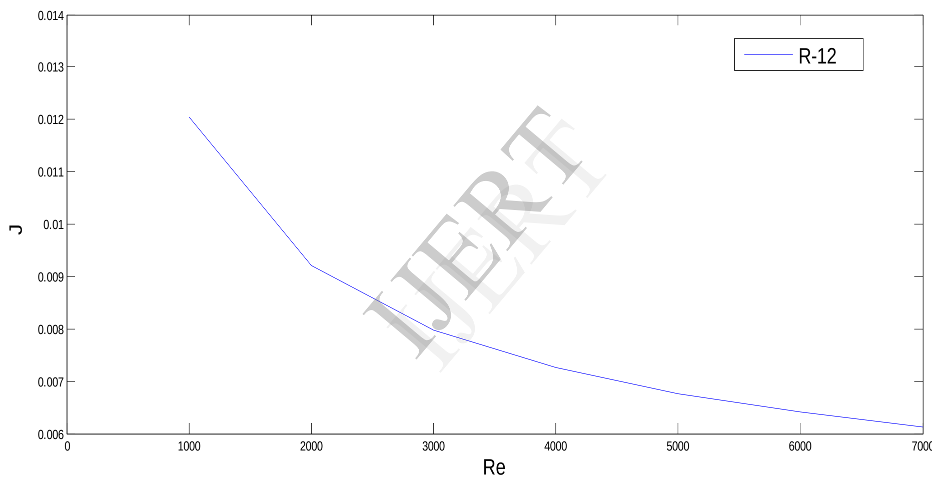

Fig.4.8: Representation of j values as a function of the Prandtl number with working fluid R-12 vs. Re on the basis of hydraulic diameter for offset-strip fin #18.

For 25% < β < 30%.

The graphical results obtained for the analysis of j factor with working fluid air, mercury, noble gas and R-12.

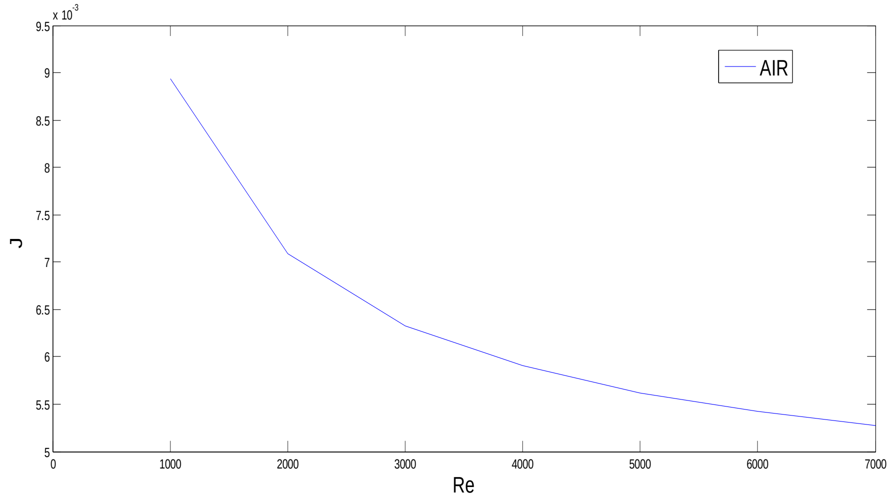

Fig.4.9: *Representation of j values as a function of the Prandtl number with working fluid air vs. Re on the basis of hydraulic diameter for offset-strip fin #22*

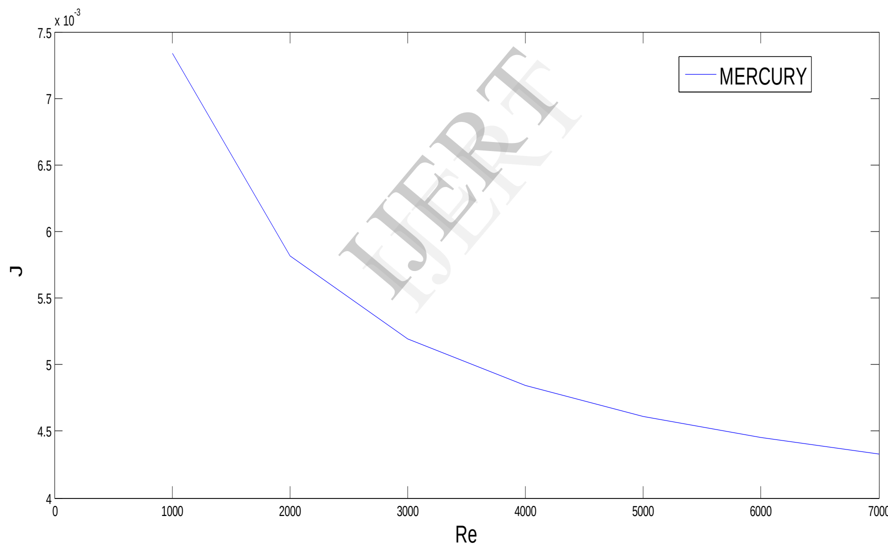

Fig.4.10: *Representation of j values as a function of the Prandtl number with working fluid mercury vs. Re on the basis of hydraulic diameter for offset-strip fin #22.*

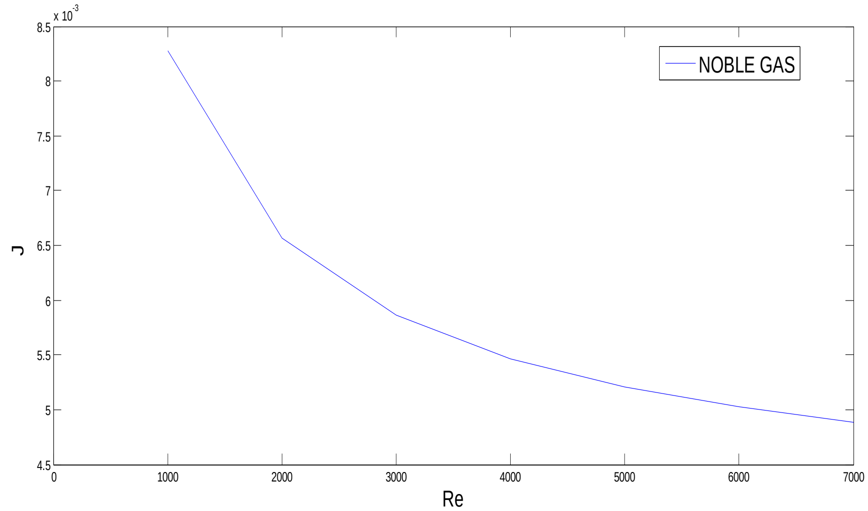

Fig.4.11: *Representation of j values as a function of the Prandtl number with working fluid noble gas vs. Re on the basis of hydraulic diameter for offset-strip fin #22.*

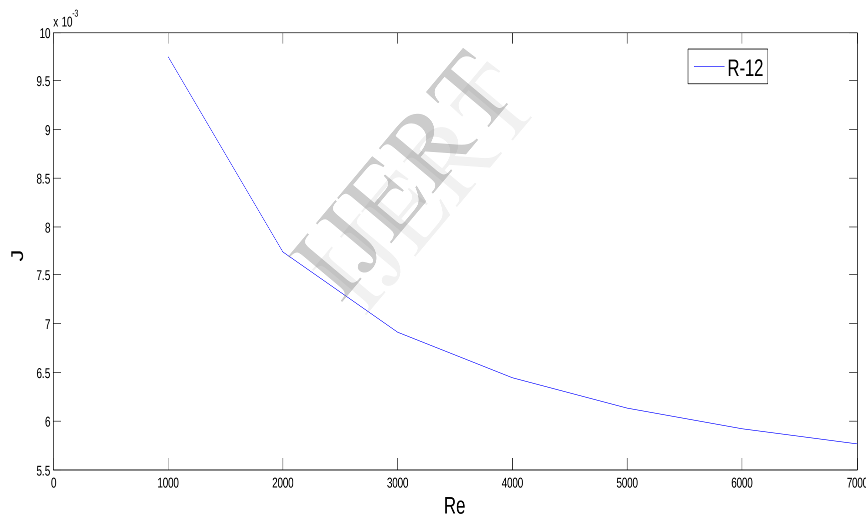

Fig.4.12: *Representation of j values as a function of the Prandtl number with working fluid R-12 vs. Re on the basis of hydraulic diameter for offset-strip fin #22.*

5. RESULTS & DISCUSSION

Numerical simulation computed for j values. The flow and thermal characteristics of the offset-strip fins were investigated according to the fin geometries and the working fluids namely air, noble gas, mercury, and R-12 are shown below in my work.

Table 5.1- For blockage ratio less than 20% with Reynolds number 1000

Sr. no	Blockage ratio	Working fluid	Value of j	Reynolds number
1	β<20%	Air	0.0138	1000
2	β<20%	Mercury	0.0137	1000
3	β<20%	Noble Gas	0.0135	1000
4	β<20%	R-12	0.0139	1000

Table 5.2- For blockage ratio 20 %< β<25% with Reynolds number 1000

Sr. no	Blockage ratio	Working fluid	Value of j	Reynolds number
1	20%<β<25%	Air	10.8×10^{-3}	1000
2	20%<β<25%	Mercury	9.59×10^{-3}	1000
3	20%<β<25%	Noble Gas	8.8×10^{-3}	1000
4	20%<β<25%	R-12	0.0122×10^{-3}	1000

Table 5.3- For blockage ratio 25%<β<30% with Reynolds number 1000

Sr. no	Blockage ratio	Working fluid	Value of j	Reynolds number
1	25%<β<30%	Air	8.59×10^{-3}	1000
2	25%<β<30%	Mercury	8.26×10^{-3}	1000
3	25%<β<30%	Noble Gas	1.4×10^{-3}	1000
4	25%<β<30%	R-12	9.58×10^{-3}	1000

Table 5.4- For blockage ratio less than 20% with Reynolds number 7000.

Sr. no	Blockage ratio	Working fluid	Value of j	Reynolds number
1	β<20%	Air	0.0077	7000
2	β<20%	Mercury	0.0075	7000
3	β<20%	Noble Gas	0.0078	7000
4	β<20%	R-12	0.0079	7000

Table 5.5- For blockage ratio 20 %< β<25% with Reynolds number 7000

Sr. no	Blockage ratio	Working fluid	Value of j	Reynolds number
1	20%<β<25%	Air	5.5×10^{-3}	7000
2	20%<β<25%	Mercury	4.5×10^{-3}	7000
3	20%<β<25%	Noble Gas	5×10^{-3}	7000
4	20%<β<25%	R-12	0.0067	7000

For blockage ratio 25%<β<30% with Reynolds number 7000

Sr. no	Blockage ratio	Working fluid	Value of j	Reynolds number
1	25%<β<30%	Air	5.27×10^{-3}	7000
2	25%<β<30%	Mercury	4.27×10^{-3}	7000
3	25%<β<30%	Noble Gas	4.59×10^{-3}	7000
4	25%<β<30%	R-12	5.55×10^{-3}	7000

6. CONCLUSION:

The flow and thermal characteristics of offset-strip fins were numerically investigated for various fin geometries and working fluids, and general correlations of the offset-strip fins were derived. Previous correlations [6] could be applied only to the offset-strip fins with blockage ratios of less than 20%. As the blockage ratio increased, the correlations began to underestimate the f values in all flow regimes. Therefore, new correlations for offset-strip fins with blockage ratios of greater than 20% were determined. Since most previous correlations are limited to air as the working fluid, this study considered various working fluids. The f values predicted by the correlations of this study did not change as the working fluid changed. However, the j values varied according to the working fluid. Therefore, new j correlations were suggested as functions of the Prandtl number. General correlations for various fin geometries were suggested in the laminar, transition, and turbulent regimes and could be available in wide ranges of blockage ratios and Prandtl numbers, i.e., β<35% and 0.72<Pr<50.

7. SCOPE FOR FUTURE WORK

The present work is concerned with the development of the correlations for determining the ***j* factor** for blockage ratio up to 35% in order to investigate the **heat transfer characteristics**; using various working fluids. The correlations can be developed for the determination of ***f* factor** for blockage ratio up to 35% in order to investigate the flow friction characteristics using various working fluids whereas, presently, the correlation for f factor is available for air as working fluid only.

In this work, the correlations developed for the ***j* factor** as a function of Prandtl number is analysed for different working fluids. Other dimensionless numbers could be used to check if use of any other dimensionless number could yield better results.

In this work, only four substances were used as working fluids i.e. air, mercury, noble gas and R-12; to test the correlations developed. The computer simulation using MATLAB generated the experimental results and confirmed the correlations. The correlations could be tested on various other working fluids which may include various oils, organic chemicals and gases etc.

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