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Performance evaluation using exergy analysis—application to wire-coil inserts in forced convection heat transfer

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Abstract—Performance of several wire-coil inserts in augmentation of convective heat transfer has been studied. A performance evaluation method based on exergy analysis has been used. The heat transfer and flow-friction characteristics which are necessary for exergy analysis are obtained experimentally. It is seen that the minimum exergy destruction criterion results in a thermodynamically optimum choice. However, heat transfer improvement number and exergy destruction number provide realistic criteria for comparing the performance of augmentation devices. Results of the performance evaluation for 12 different wire-coil inserts with $d/D = 0.058$–0.113 and $p/D = 0.202$–0.605 are presented in turbulent flow regions for $Re = 30\,000$–$120\,000$.

INTRODUCTION

HEAT transfer augmentation [1] provides a simple and economical method of improving the thermal performance of heat exchangers. The use of such a technique results in a reduced surface area requirement and consequently a smaller heat exchanger and reduced equipment cost. Various types of augmentation devices have been developed in the past [2]. It is, therefore, necessary to be able to compare the performance of these devices in order to select the most suitable one for a given operating condition. In this paper, performance of wire-coil inserts, which can be used to upgrade the performance of an existing heat exchanger [3], has been evaluated using an exergy analysis method proposed earlier [4]. In this method, the heat transfer characteristics (Nu–Re) and the flow-friction characteristics (f–Re) of the competing augmentation devices are required in order to calculate the combined exergy destruction due to finite temperature difference and flow-friction. The thermodynamic optimum is, thus, obtained by minimizing the exergy destruction. Furthermore, there are only a few correlations [2, 3, 5, 6] for Nusselt number (Nu) and friction factor (f) for wire-coil inserts. An experimental study was, therefore, carried out with these inserts assembled within the inner tube of a counterflow concentric tube heat exchanger (Fig. 1). The augmented Nusselt number (Nu_a) and the augmented friction factor (f_a) for each wire-coil insert were experimentally evaluated for various Reynolds number. Nusselt numbers and friction factors for smooth tubes were also experimentally determined to ensure the accuracy of measurements as well as for comparison of the results with augmented cases.

In addition to using the minimum exergy destruction criterion which results in a thermodynamic optimum, other criteria such as heat transfer enhancement number and exergy destruction number are also useful in order to compare various devices and choose a particular augmentation device for a given operating condition.

EXERGY ANALYSIS

In heat transfer systems such as a tubular fluid to fluid heat exchanger (Fig. 1), the net exergy destruction consists of two parts: the destruction due to heat transfer across a finite temperature difference and the destruction due to flow-friction. The use of an augmentation device results in an improved heat transfer coefficient and, therefore, reduced exergy destruction due to heat transfer. However, the presence of an augmentation device presents additional resistance to fluid flow resulting in an increase in exergy destruction due to frictional effects. The net exergy destruction is, thus, used as a performance evaluating criterion. The minimum exergy destruction represents a thermodynamic optimum condition.

NOMENCLATURE

c	specific heat [J kg^{-1} K^{-1}]
CPI	coils per inch
d	wire diameter [m, mm, in.]
D	diameter of pipe [m]
f	friction factor
h	heat transfer coefficient [W m^{-2} K^{-1}]
k	thermal conductivity [W m^{-1} K^{-1}]
L	length of test section [m]
M	mass flow rate [kg s^{-1}]
N_E	exergy destruction number
N_H	heat transfer enhancement number
Nu	Nusselt number
p	pressure [N m^{-2}]
Q	heat [J s^{-1}, W]
Re_d	Reynold's number based on d
s	entropy [J kg^{-1} K^{-1}]
SBr	pseudo Brinkman number
T	temperature [K]
v	specific volume [m^3 kg^{-1}]
V	velocity [m s^{-1}]
w	perimeter of the duct or tube [m]
x	distance along the length of heat exchanger [m].

Greek symbols

ψ	specific flow-exergy [J kg^{-1}]
Ψ	flow-exergy [J]
$\Delta\Psi$	flow-exergy destruction [J]
$\Delta\Psi^*$	dimensionless flow-exergy destruction
γ	defined in equation (3)
μ	coefficient of viscosity [kg m^{-1} s^{-1}]
ρ	density [kg m^{-3}]
τ	defined in equation (8).

Subscripts

0	reference state
1	inlet
a	augmented
p	constant pressure
s	smooth
w	wall
x	at x.

The exergy analysis employed here is based on a tubular heat exchanger (Fig. 2) in which the tube wall is assumed to be at a constant temperature T_w. The heat exchanging fluid flowing inside this tube is liquid, with temperature distribution $T(x)$ represented by [4]:

$$T(x) = T_w + \Delta T_1 \, e^{-\gamma x}, \tag{1}$$

where:

$$\Delta T_1 = T_1 - T_w, \tag{2}$$

and:

$$\gamma = \frac{hw}{Mc_p}. \tag{3}$$

The fluid properties are assumed to be constant. Using the definition of specific flow exergy ψ:

$$\psi = h - h_0 - T_0\,(s - s_0), \tag{4}$$

and considering that:

$$\psi = \psi(T,P), \tag{5}$$

together with the definition of entropy, specific heat

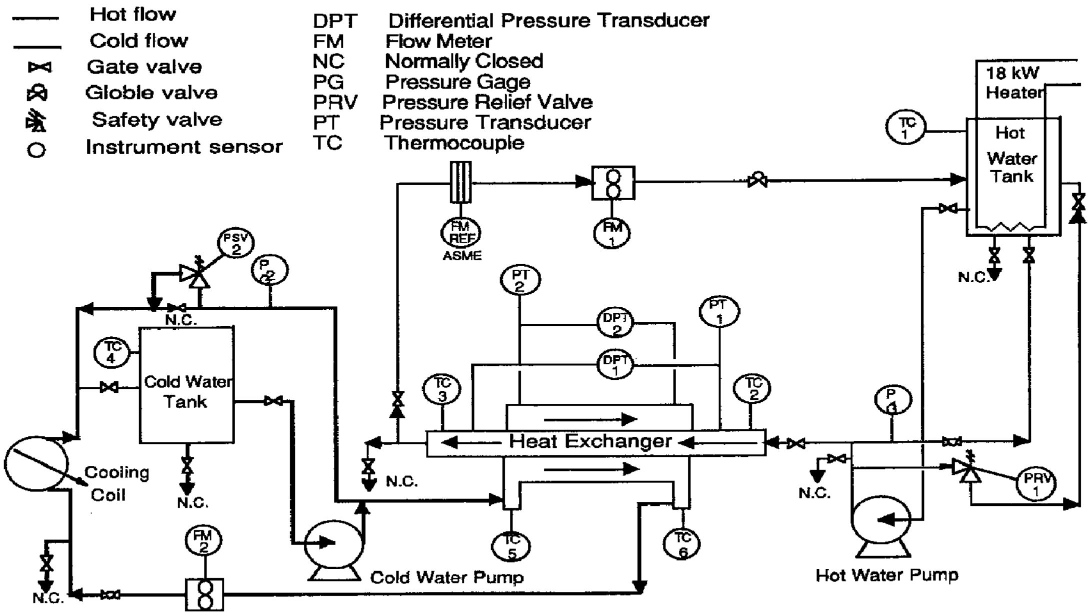


FIG. 1. Schematic diagram of experimental set-up with a tubular heat exchanger.

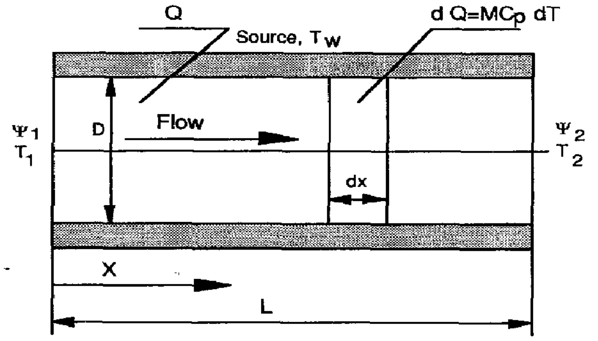


FIG. 2. Schematic diagram of a single-tube heat exchanger.

and the first law of thermodynamics, the dimensionless exergy destruction $\Delta\Psi^*$ in this case can be expressed by [4]:

$$\Delta\Psi^* = \left[\tau(1-e^{-\gamma L}) + \ln\left(\frac{1+\tau e^{-\gamma L}}{1+\tau}\right)\right] + \left[\frac{f Re\, SBr}{8Nu}\ln\left(\frac{1+\tau e^{-\gamma L}}{(1+\tau)e^{-\gamma L}}\right)\right], \quad (6)$$

where:

$$\Delta\Psi^* = \frac{\Delta\Psi}{MT_0 c_p}, \quad (7)$$

$$\tau = \frac{\Delta T_1}{T_w}, \quad (8)$$

$$SBr = \frac{\mu V^2}{kT_w}. \quad (9)$$

The Nusselt number and friction factor in the case of augmented tubes were obtained experimentally in a desired range of Reynolds number. The exergy destruction was calculated for all the augmentation devices using equation (6) in the experimental range of Reynolds number. Results obtained from the experimental tests for Nusselt number and friction factor are presented in next section.

APPLICATION TO WIRE-COIL INSERTS

The experimental system

The experimental apparatus used in this study is briefly described in ref. [4] and is shown in Fig. 1. It consisted of a concentric-tube heat exchanger, constructed with 14 mm (I.D.) and 26 mm (I.D.) copper tubes, with a 2.2 m long test section. The sealing fixtures provided the necessary seal around the inner tube and maintained the concentricity of the tubes. Two spiders with three radial pins were inserted on the inner tube to prevent it from sagging. The test section was insulated to minimize any heat exchange with the environment. The circulation system provided a true counterflow heat exchange in the test section. Hot water from a 100-gallon stainless tank maintained at 30–50°C by a solid-state controlled 18-kW electric heater was circulated by a 5 HP turbine pump through the inner tube. Cold water at 10–20°C was circulated through the annular space by a 3 HP multistage turbine pump. The cold water leaving the test section was cooled by a coil-in-coil cooler before returning to the cold water reservoir, another 100-gallon stainless steel tank.

The wire-coil inserts of four different pitch were constructed with stainless steel wires of three different diameters. In order to prevent the movement of the coils during the tests, the coil was silver soldered to a thin wire running longitudinally along the tube. The dimensions of the wire-coil inserts are given in Table 1.

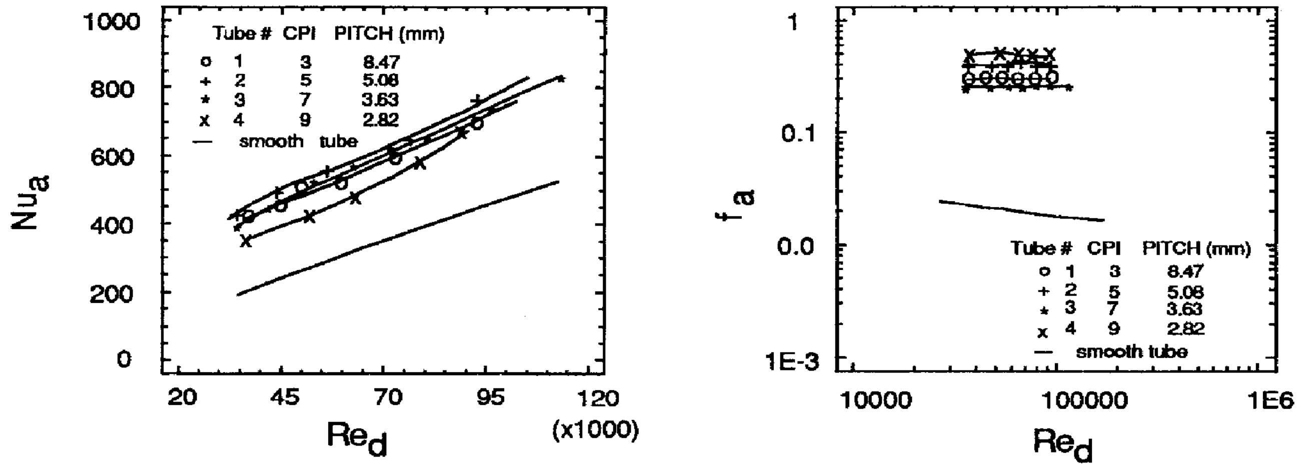
The experimental system was instrumented with thermocouples (T-type), pressure transducers (CELESLO P7D) and flow meters (SIGNET-MK525) for computerized measurement of fluid temperature, pressure and pressure loss, and fluid flow rate, respectively. These sensors were calibrated with reference to primary/secondary standards. An on-line computer (HP VECTRA ES/12) together with a data-acquisition system (HP 3497A) was used for computerized data-acquisition and data processing.

Tests with augmented tubes

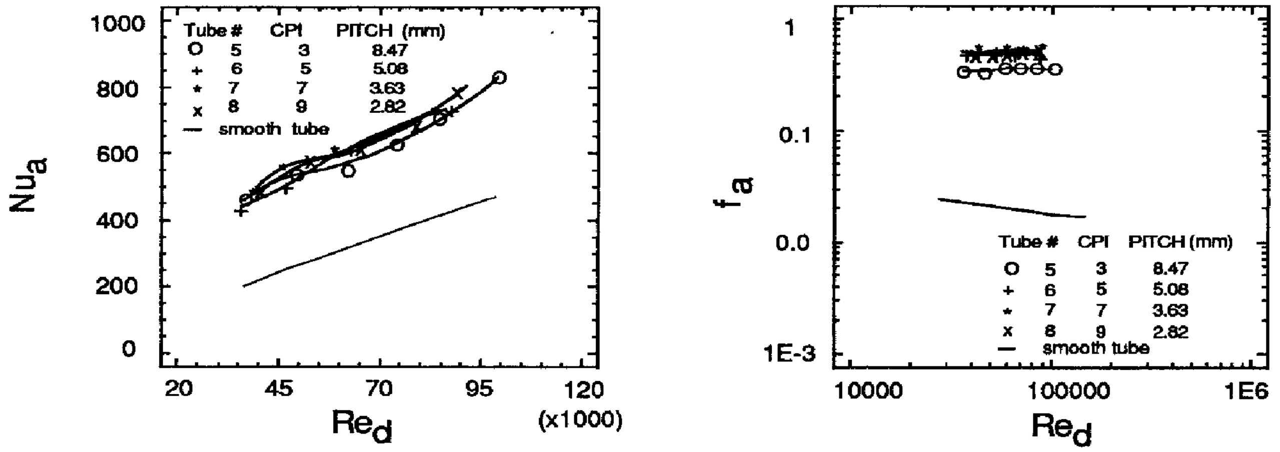
Experimental tests were carried out with 12 different wire-coil inserts and their heat transfer and flow-friction characteristics were obtained. The heat transfer characteristic was shown by augmented Nusselt number (Nu_a) as a function of Reynolds number. The

Table 1. Characteristic dimensions of wire-coil inserts

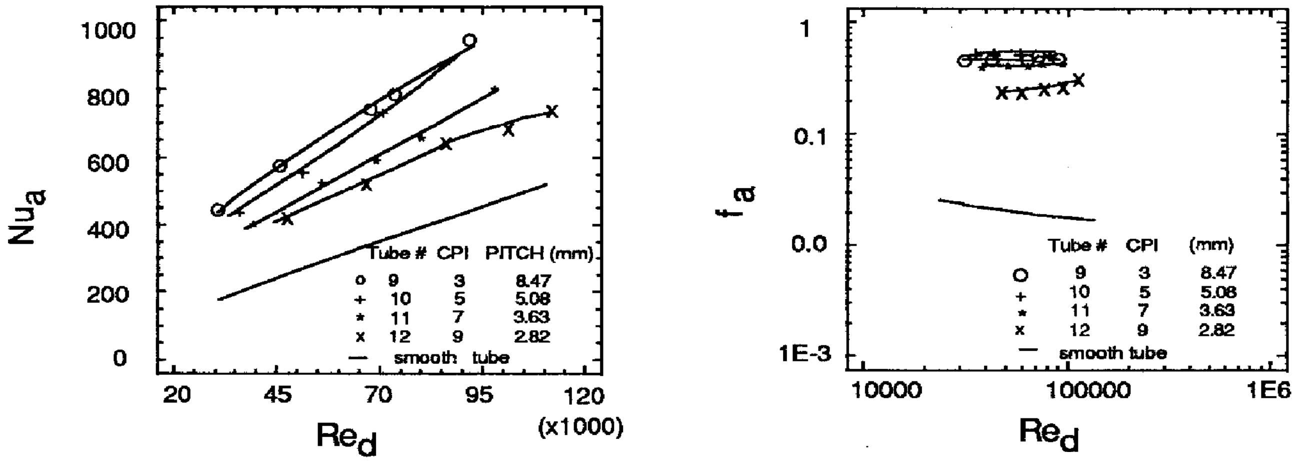
Tube #	Wire diameter, *d* (mm)	Coil pitch, *p* (mm)	Coils per inch, *CPI*
1	0.813	8.47	3
2	0.813	5.08	5
3	0.813	3.63	7
4	0.813	2.82	9
5	1.016	8.47	3
6	1.016	5.08	5
7	1.016	3.63	7
8	1.016	2.82	9
9	1.575	8.47	3
10	1.575	5.08	5
11	1.575	3.63	7
12	1.575	2.82	9



(a) Nu for d = 0.813 mm (0.032 inch) (b) f for d = 0.813 mm (0.032 inch)

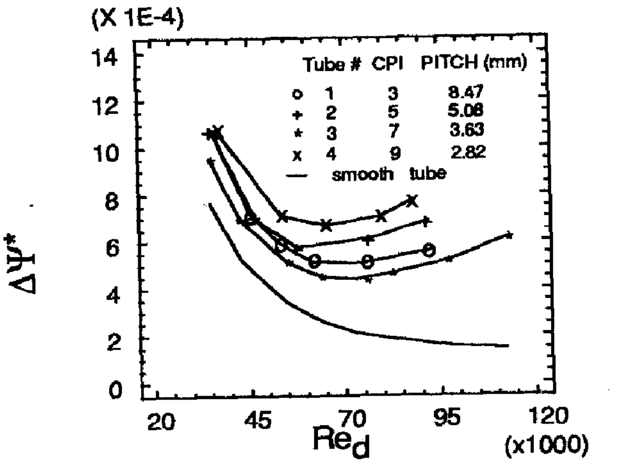


(c) Nu for d = 1.016 mm (0.040 inch) (d) f for d = 1.016 mm (0.040 inch)

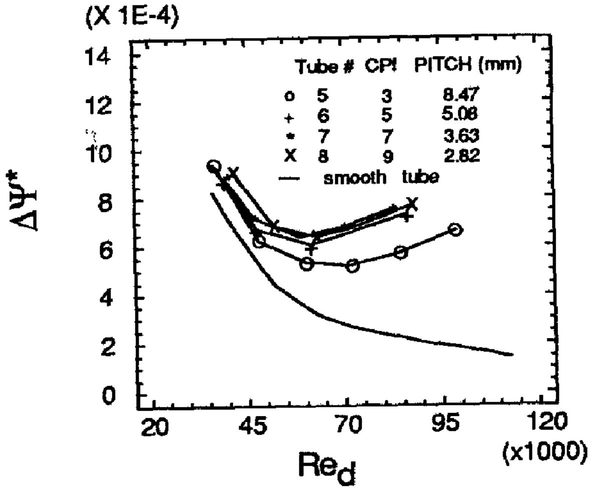


(e) Nu for d = 1.575 mm (0.062 inch) (f) f for d = 1.575 mm (0.062 inch)

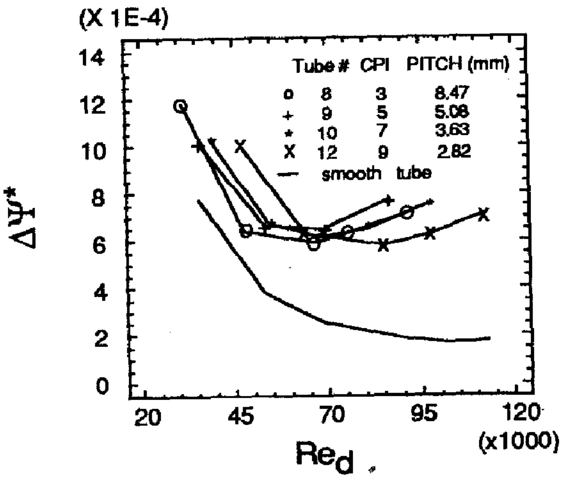
FIG. 3. Augmented Nusselt number and friction factor for wire-coil inserts: (a) Nusselt number for $d = 0.813$ mm (0.032 in.); (b) friction factor for $d = 0.813$ mm (0.032 in.); (c) Nusselt number for $d = 1.016$ mm (0.040 in.); (d) friction factor for $d = 1.016$ mm (0.040 in.); (e) Nusselt number for $d = 1.575$ mm (0.062 in.); and (f) friction factor for $d = 1.575$ mm (0.062 in.).



(a) d = 0.813 mm (0.032 inch)

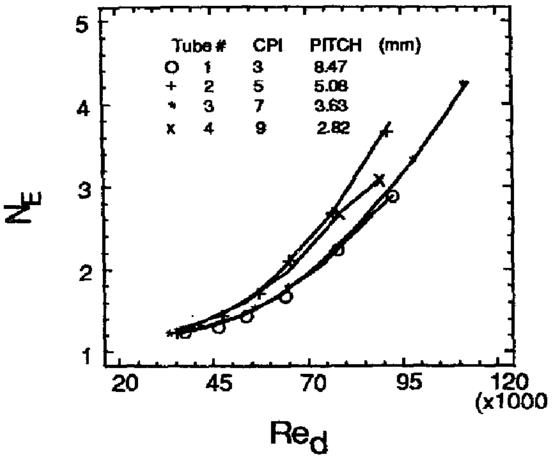


(b) d = 1.016 mm (0.040 inch)

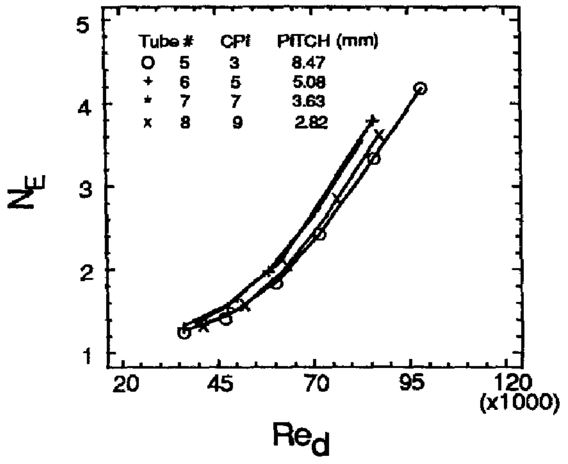


(c) d = 1.575 mm (0.062 inch)

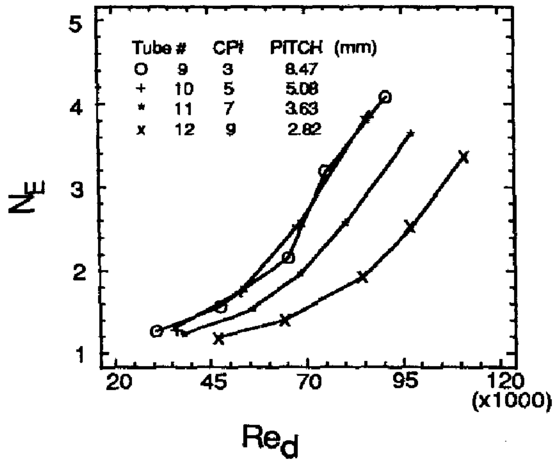
FIG. 4. Dimensionless exergy destruction for wire-coil inserts: (a) $d = 0.813$ mm (0.032 in.); (b) $d = 1.016$ mm (0.040 in.); and (c) $d = 1.575$ mm (0.062 in.).



(a) d = 0.813 mm (0.032 inch)

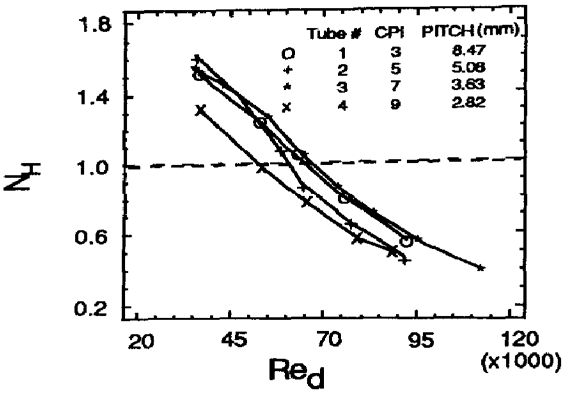


(b) d = 1.016 mm (0.040 inch)

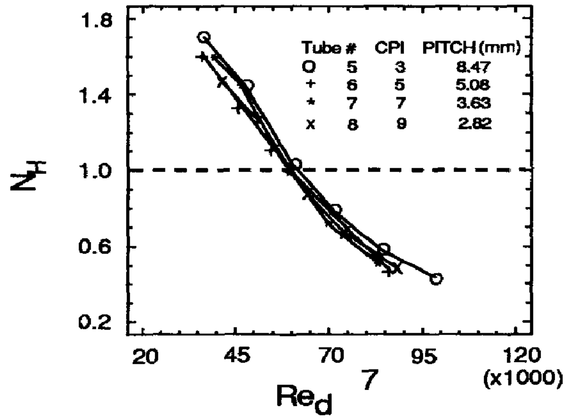


(c) d = 1.575 mm (0.062 inch)

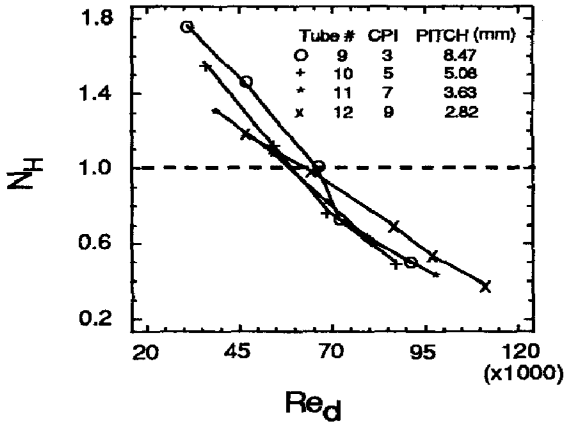
FIG. 5. Exergy destruction number for wire-coil inserts: (a) $d = 0.813$ mm (0.032 in.); (b) $d = 1.016$ mm (0.040 in.); and (c) $d = 1.575$ mm (0.062 in.).



(a) d = 0.813 mm (0.032 inch)



(b) d = 1.016 mm (0.040 inch)



(c) d = 1.575 mm (0.062 inch)

FIG. 6. Heat transfer enhancement number for wire-coil inserts: (a) $d = 0.813$ mm (0.032 in.); (b) $d = 1.016$ mm (0.040 in.); and (c) $d = 1.575$ mm (0.062 in.).

frictional nature of these inserts were seen from the augmented Darcy friction factor (f_a) as a function of Reynolds number. Full details of the procedure of calculating Nu_a and f_a from the experimental data are outlined in ref. [7]. These results are shown in Fig. 3. Figure 3a, c and e show Nu_a–Re and Fig. 3b, d and f show f_a–Re for wire-coil inserts used in this work. In all these figures, the characteristics of the smooth tube are also shown for comparison with the augmented tubes.

With these experimental Nu_a and f_a for the test wire-coil inserts, the dimensionless exergy destruction $\Delta\Psi^*$ can be determined from equation (6).

PERFORMANCE EVALUATION

In a heat exchanger with a heat transfer augmentation device, the exergy destruction from finite temperature difference decreases while that due to frictional effects increases. It is, thus, possible to determine the thermodynamic optimum in a heat exchanger with fixed geometrics by minimizing the exergy destruction. Figure 4 shows $\Delta\Psi^*$–Re for all the tests conducted in this study, and the optimum Reynolds number corresponding to minimum exergy destruction can be obtained in each case. However, the augmented system would be thermodynamically advantageous only if the exergy destruction number, N_E, defined by:

$$N_E = \Delta\Psi_a^*/\Delta\Psi_s^*, \qquad (10)$$

is less than unity. This would mean that the reduction in exergy destruction due to improved heat transfer more than offsets the increased exergy destruction due to the augmentation device. Unfortunately, this is not always the case and N_E, in the present study with wire-coil inserts is greater than unity since the irreversibility in the system is essentially dominated by flow-friction rather than heat transfer. What is pursued here is whether the ratio Nu^* defined by:

$$Nu^* = Nu_a/Nu_s, \qquad (11)$$

which is indicative of the improvement in heat transfer, is larger than N_E, an indicator of the destruction of exergy. If this is the case, the heat transfer improvement number, N_H, defined by:

$$N_H = Nu^*/N_E, \qquad (12)$$

is greater than unity and the augmented heat exchanger is also effective and acceptable from the view point of improving heat transfer. In summary, the following three goals are sought:

(1) $\Delta\Psi^*$ is minimum;
(2) exergy destruction number N_E is less than or equal to unity; and
(3) heat transfer improvement number N_H is larger than unity.

Exergy destruction number N_E and heat transfer improvement number N_H for the wire-coil inserts studied here are shown in Figs. 5 and 6, respectively. In Fig. 5, it is seen that the exergy loss number (N_E) is greater than unity and increases with Reynolds number for all the augmented tubes. This indicates that the heat transfer enhancement with these devices is always associated with an increase of exergy destruction. These devices are, therefore, more effective at lower Reynolds numbers in comparison to higher Reynolds numbers. This conclusion can also be drawn from the heat transfer improvement number (N_H) shown in Fig. 6. For $Re < 50\,000$, N_H is larger than unity which indicates that the relative increase in heat transfer is greater than the corresponding exergy destruction with reference to a smooth tube. The condition $N_H > 1$ thus means that the augmentation system is effective and thermodynamically acceptable. At higher Reynolds number, N_H becomes less than unity indicating a less preferable situation. The most effective wire-coil insert among the twelve cases studied in this work is tube #9 ($d = 1.575$ mm, $p = 8.47$ mm) since it has the highest heat transfer improvement number (N_H) at Reynolds number less than 68 000.

CONCLUSIONS

A method for performance evaluation of convective heat transfer augmentation devices is presented. The method is based on exergy analysis and utilizes two non-dimensional parameters—exergy destruction number (N_E) and heat transfer improvement number (N_H)—as performance evaluating criteria. These numbers permit a comparison of the effect of improved heat transfer with increased irreversibility due to a heat transfer augmentation device and, thus, provide effective and thermodynamically acceptable criteria. The method has been applied to wire-coil inserts as augmentation devices in forced convection heat transfer. Nusselt number and friction factor data for these augmentation devices were obtained experimentally and utilized in the performance evaluation presented here.

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