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# EFFECT OF MATRIX SPEED ON EFFECTIVENESS OF ROTARY-TYPE HEAT EXCHANGER

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## ABSTRACT

In this paper, the effect of matrix speed on the effectiveness of a rotary heat exchanger is investigated. The effectiveness is obtained analytically, numerically and experimentally. The experimental results are compared with the analytical and numerical ones. It is found that there is a good agreement between the results.

## 1. INTRODUCTION

There are two types of heat exchangers commonly used for waste heat recovery, these are recuperators and regenerators. Regenerator type heat exchangers are divided into two groups which are valved-type and rotary-type.

Rotary-type heat exchangers have a porous matrix and transfer heat between two gas streams. These types have various application areas and mostly used for waste heat recovery. The porous matrix is arranged in the form of a drum which rotates about an axis, so that the body of the porous matrix passes periodically through the hot stream and then through the cold stream. The heat which is stored in the porous matrix during its contact with the hot gas is transferred to the cold gas during its contact with the cold stream. Knowing the variation of effectiveness with the rotational speed of a rotary regenerator is important to get the maximum benefit from it and for capacity and, therefore, automatic control.

In this study, rotary-type heat exchangers are considered. Experiments were performed using a laboratory made rotary-type regenerator in order to test the influence of matrix speed on effectiveness. For the same regenerator, and for the same parameters, the effectiveness was also calculated with the help of analytical equations developed by one

of the present authors in a previous study. In addition, a numerical study was carried out to obtain the effectiveness. Analytical, numerical and experimental studies are given below.

## 2. ANALYTICAL STUDY

In this study, analytical results for the effectiveness ($\varepsilon_a$) was obtained using the equation given by Kays and London (1984):

$$\varepsilon_a = \varepsilon_o \varphi_r \varphi_c \tag{1}$$

in which, $\varepsilon_o$ denotes the effectiveness of a cross-flow heat exchanger, $\varphi_r$ is a correction factor for rotational speed and $\varphi_c$ represents a correction factor for cleaning region.

Effectiveness of a cross-flow heat exchanger can be calculated using equation (2) suggested by Kays and London (1984):

$$\varepsilon_o = \frac{1 - e^{[-Ntu(1-C^*)]}}{1 - C^* e^{[-Ntu(1-C^*)]}} \tag{2}$$

As can be seen from this equation, $\varepsilon_o$ depends on two parameters which are the heat capacity ratio ($C^*$) and the number of transfer units (Ntu). These parameters are defined as:

$$C^* = \frac{C_{min}}{C_{max}} \tag{3}$$

$$Ntu = \frac{kF}{C_{min}} \tag{4}$$

Heat capacity of a heat exchanger (kF) is calculated from the equation given below:

$$\frac{1}{kF} = \frac{1}{\alpha_f F_f} + \frac{1}{\alpha_w F_w} \tag{5}$$

where $\alpha$ is heat transfer coefficient and can be calculated knowing the Nusselt number.

The Nusselt number was calculated using the equations developed by one of the present authors (Yılmaz and Cihan, 1993) and is given by:

$$Nu = Nu_\infty \left[ 1 + \frac{4.212 \psi \Phi^3}{Z^* Nu_\infty^3} - 0.8 \left( \frac{\psi \Phi^3}{Z^* Nu_\infty^3} \right)^{2/3} \right]^{1/3} \tag{6}$$

Kays and London (1984) suggested the equation below for the calculation of correction factor for rotational speed which depends on the heat capacity ratio of the heat exchanger ($C_r^*$):

$$\varphi_r = 1 - \frac{1}{9C_r^{*1.93}} \tag{7}$$

For the regenerator used in the experiments, there was no cleaning region, so the correction factor for cleaning region ($\varphi_c$) was taken as 1 in calculations.

### 2.1. Analytical Results

Using the equations given above, the analytical results for the effectiveness was calculated for the parameters covered in the experiments. Influence of rotational speed of the porous matrix on effectiveness can be seen from Fig. 1.

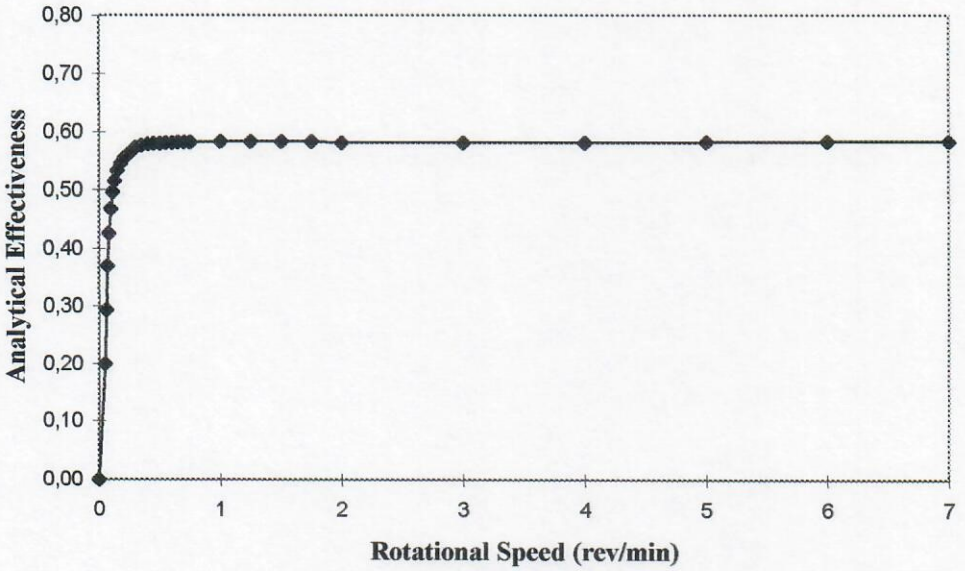



**Figure 1.** Variation with rotational speed of effectiveness obtained from the analytical equations.

It is seen from Fig. 1 that after a speed of 0.5 rev/min, the effectiveness of the rotary heat exchanger is nearly constant and it has a value of about 0.6. Below 0.5 rev/min, the effectiveness increases rapidly with the increase of rotational speed.

## 3. NUMERICAL STUDY

Numerical results were obtained by writing a mathematical model for the fluid and for the wall of the rotary heat exchanger matrix as shown in Fig. 2.

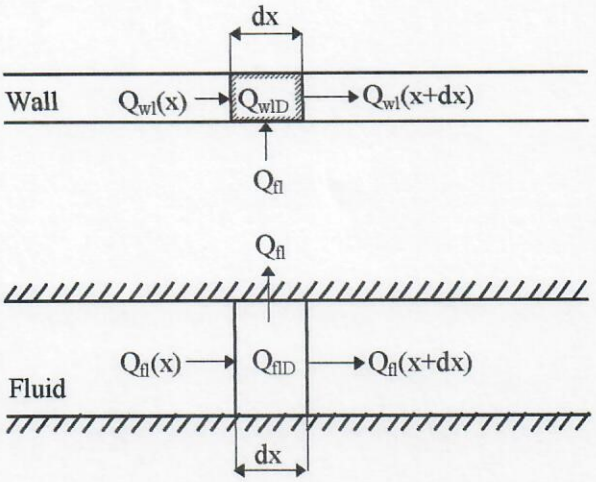



**Figure 2.** Energy balance for the unit element of rotary heat exchanger, and fluid.

Applying the first law of thermodynamics to the unit element of the wall and the fluid, differential equations for wall temperature and fluid temperature were written with some assumptions (Ünal, 1996; Yılmaz and Ünal, 1996). Dimensionless form of the equations are given below:

$$\frac{1}{R}\frac{\partial T_{fl}^*}{\partial t^*} + \frac{\partial T_{fl}^*}{\partial x^*} - \frac{Fo_{fl}}{R}\frac{\partial^2 T_{fl}^*}{\partial x^{*2}} + Ntu\, T_{fl}^* = Ntu\, T_{wl}^* \qquad \text{(for fluid)} \tag{8}$$

$$\frac{\partial T_{wl}^*}{\partial t^*} - Fo_{wl}\frac{\partial^2 T_{wl}^*}{\partial x^{*2}} + \frac{Ntu}{C_r^*}T_{wl}^* = \frac{Ntu}{C_r^*}T_{fl}^* \qquad \text{(for wall)} \tag{9}$$

For these coupled differential equations and the boundary conditions (constant temperature of cold and hot fluid at the inlet and zero conductive heat transfer on the wall at the inlet and at the outlet of the regenerator) discretization equations using finite differences are obtained. At the beginning of the calculations ($t^*=0$), we assume a constant temperature in the regenerator (a mean temperature of hot and cold fluid). We calculate first fluid temperature and then wall temperature. These calculations are carried out using a computer program written in Fortran programming language and continued until the temperature do not change in each period. From these temperatures, we calculate the effectiveness of the regenerator. Detailed information about the numerical method employed and about the influences of the different boundary conditions of the fluid at the end of the regenerator ($\partial T_{fl}^*/\partial x^* = 0$, $\partial^2 T_{fl}^*/\partial x^{*2} = 0$, $\partial T_{fl}^*/\partial x^* = \partial^2 T_{fl}^*/\partial x^{*2} = 0$) are given by Ünal (1996).

### 3.1. Numerical Results

The effectiveness ($\varepsilon_c$) of rotary regenerator was obtained by solving the differential equations with the help of boundary conditions for various rotational speeds. The effect of rotational speed of the porous matrix on the effectiveness is shown in Fig. 3.

It is seen from Fig. 3 that, after a rotational speed of 2 rev/min, the effectiveness of the rotary heat exchanger is nearly constant at about 0.55. Similar to the results obtained from the analytical study (Fig. 1), the effectiveness varies sharply with rotational speed below 1 rev/min.

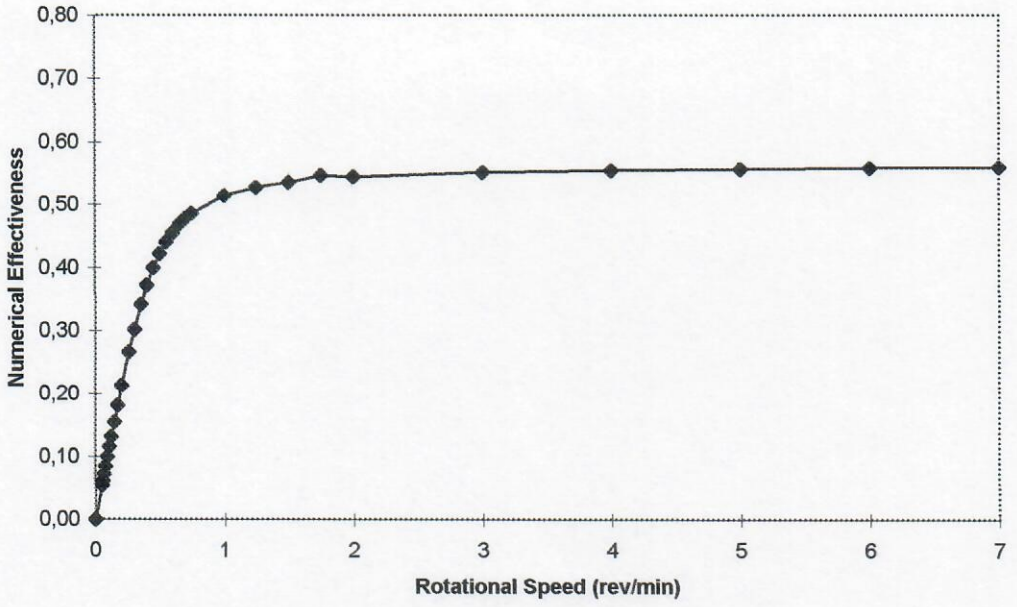



**Figure 3.** Variation with rotational speed of effectiveness obtained from the numerical equations.

## 4. EXPERIMENTAL STUDY

In this study, the effectiveness of a rotary heat exchanger was also investigated experimentally. The experimental setup is shown schematically in Fig. 4.

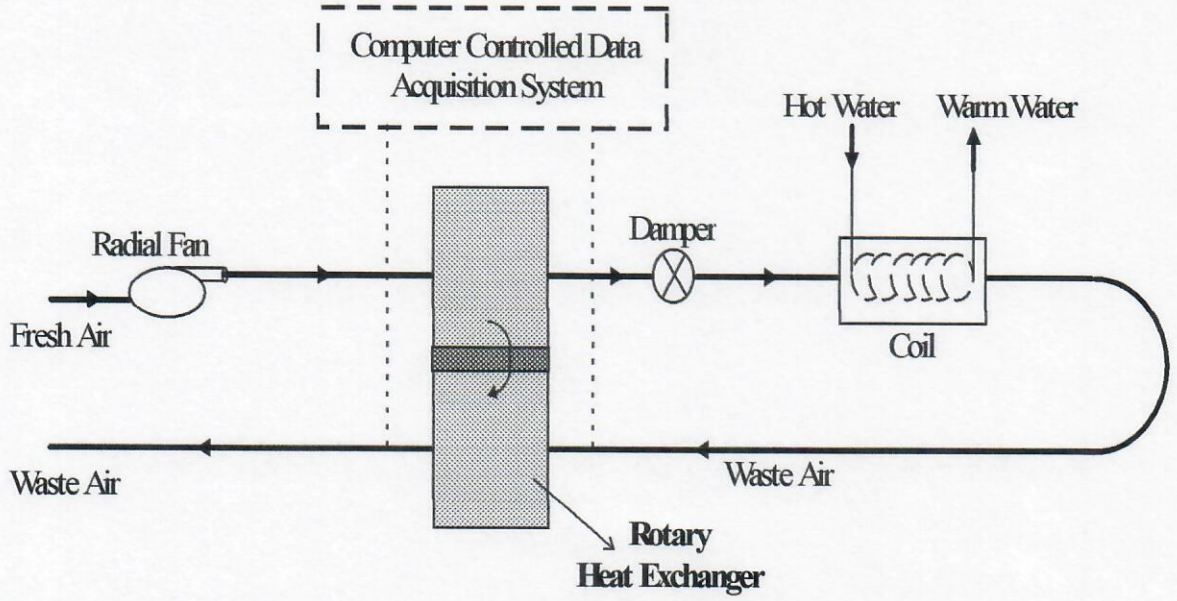



**Figure 4.** Schematic representation of experimental setup.

Fresh air is taken into the system with a radial fan. When it passes through one side of the rotary heat exchanger, it receives heat from the porous matrix. Then it passes from a damper which is used to adjust the fresh air flow rate. Pre-heated fresh air comes to a coil which is heated by a central heating system. After the coil, heated air represents waste air. The waste air leaves part of its heat to the porous matrix when it passes through the other side of the rotary heat exchanger and leaves the system. Wire sieves are used to improve the flow at various sections. The heat exchanger was rotated with the help of a AC motor and a special speed varying system was used to change the rotational speed.

Rotary-type heat exchangers are not manufactured in Turkey. Although it is possible to import them from abroad, the prices are quite high. Thus, a rotary-type heat exchanger was manufactured in the Laboratories of Çukurova University Mechanical Engineering Department to use in the experimental studies.

The flow passage of the porous matrix of the rotary heat exchanger is shown schematically in Fig. 5. Flow passage geometries have an equilateral structure. The length of one side is approximately 3.44 mm. Matrix material is aluminum and the plate thickness is 0.35 mm.

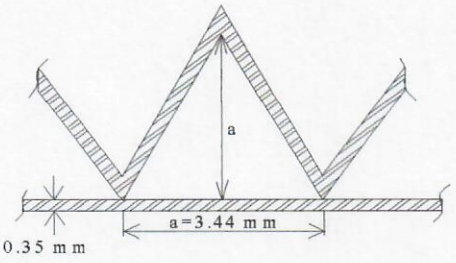



**Figure 5.** Flow passage geometry of the rotary heat exchanger used in the experiments.

During the experiments fresh and waste air flow rates and temperatures and, heat exchanger rotational speed were measured. Temperature measurements were performed with K-type thermocouples at the inlet and the outlet of both sides of the rotary heat exchanger. Nine thermocouples were located into the channels and they were arranged to give average temperature at that section. A computer controlled data acquisition system was used to collect data.

Fresh air inlet temperature was kept constant at about 20 °C during the experiments, and waste air temperature was varied between 33 °C to 42 °C. Due to the experimental arrangement utilised in this study, the waste air flow rate is approximately equal to that of fresh air and it is 1.042 $m^3/s$. A series of experiments were performed at various rotational speeds between 0.05 rev/min and 7 rev/min.

Using the data obtained from the experiments $\varepsilon_e$ was calculated from its definition:

$$\varepsilon_e = \frac{Q}{Q_{max}} \tag{10}$$

Here, Q is the actual heat transfer rate:

$$Q = C(T_{outlet} - T_{inlet}) \tag{11}$$

and $Q_{max}$ is maximum possible heat transfer rate from one stream to the other:

$$Q_{max} = C_{min}(T_{w,inlet} - T_{w,outlet}) \tag{12}$$

### 4.1. Experimental Results

In the experiments, various rotational speeds were covered in the range of 0.05 rev/min and 7 rev/min. Results are shown in Fig. 6.

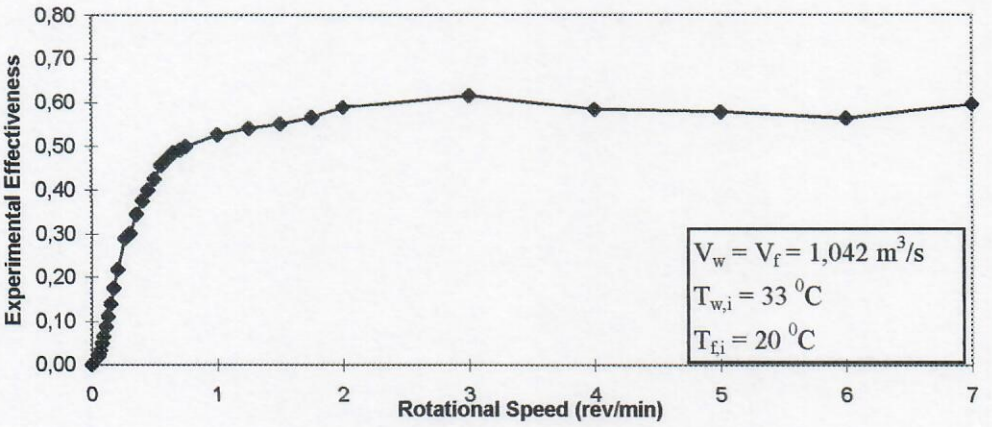



**Figure 6.** Variation with rotational speed of effectiveness obtained from the experiments.

Although there is a ±5% variation in effectiveness with rotational speed above 2 rev/min, it is not systematic and is believed to be due to experimental errors. In this region, the effectiveness is almost constant and it has a value of 0.56. The sharp increase of effectiveness with rotational speed in the low speed region can also be seen in this case.

The results of the experiments with other waste air inlet temperatures showed that they have no considerable influence on the effectiveness of rotary regenerator for the parameter range covered in the experiments.

## 5. COMPARISION and DISCUSSION

Fig. 7 compares the effectiveness obtained from the analytical, the numerical and the experimental studies.

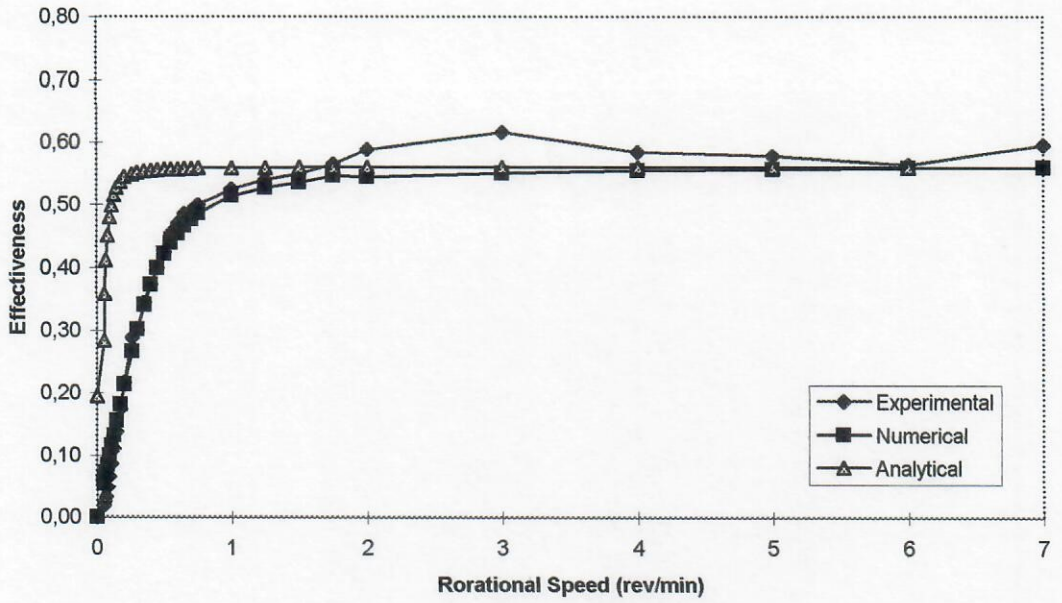



**Figure 7.** Comparison of effectiveness obtained from the analytical, the numerical and the experimental studies.

A good agreement between the results for the region in which rotational speed is higher than 2 rev/min is evident from Fig. 7. The experimental results almost coincide with the numerical ones in the low rotational speed region (0-1 rev/min). In this region, however, the analytical effectiveness is significantly higher than the others.

In the analytical calculations, the influence on effectiveness of the rotational speed is taken into account with a correction factor, $\varphi_r$ and in the study, it was obtained using the Eqn. 7 given by Kays and London (1984).

The fact that the analytical effectiveness is higher than the experimental and numerical ones suggests that Eqn. 7 can not predict correctly the influence of rotational speed on effectiveness for low rotational speeds. A new correction factor for rotational speed was determined with the help of Fig. 7 and it is:

$$\varphi_r = \frac{0.24C_r^*}{\left[1 + 0.02C_r^{*1.82} + \left(0.24C_r^*\right)^3\right]^{1/3}} \qquad \textbf{(13)}$$

Using the new $\varphi_r$, the effectiveness is calculated and is shown in Fig. 8. The good agreement between the results suggests that the influence of rotational speed can successfully be predicted by Eqn. 13.

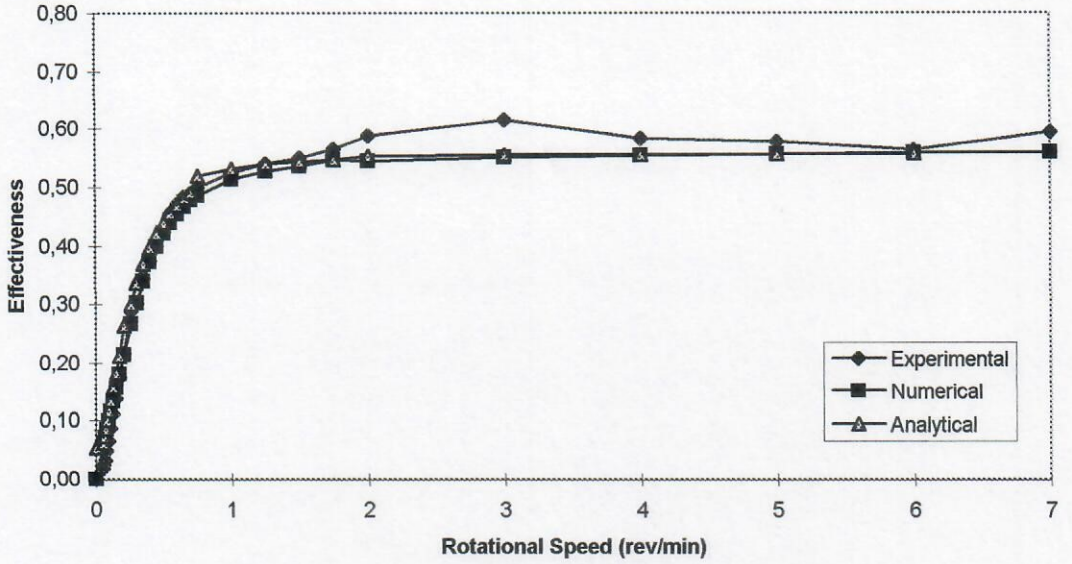



**Figure 8.** Comparison of effectiveness obtained from the new analytical formula, numerical and experimental studies.

## 6. CONCLUSION

In this study, the influence of matrix speed on effectiveness of a rotary-type heat exchanger is obtained analytically, numerically and experimentally.

For the high matrix speeds (2-7 rev/min) all of the results were found to be in good agreement. However, for the low matrix speeds (0-1 rev/min) the analytical effectiveness results obtained using the correction factor for rotational speed suggested by Kays and London (Eqn. 7) was higher than the others. A new correction factor (Eqn. 13) was obtained to describe the influence of rotational speed and it was seen that the effectiveness calculated using this new correction factor produced results that were in good agreement with the experimental and the computational ones.

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## SYMBOLS

| | |
|---|---|
| $\varepsilon$ | : Effectiveness |
| $\varphi_r$ | : Correction factor for rotational speed |
| $\varphi_c$ | : Correction factor for cleaning region |
| $Ntu$ | : Number of transfer units |
| $C$ | : Heat capacity |
| $k$ | : Overall heat transfer coefficient |
| $F$ | : Heat transfer surface area |
| $\psi$ | : Shape factor for developed flow |
| $\Phi$ | : Heat transfer factor |
| $z^*$ | : Dimensionless coordinate |
| $R$ | : Mass rate factor |
| $Q$ | : Heat transfer rate |
| $T$ | : Temperature |
| $t$ | : Time |
| $\dot{V}$ | : Volume flow rate |

**Subscripts**

| | |
|---|---|
| $a$ | : Analytical |
| $c$ | : Numerical |
| $e$ | : Experimental |
| $o$ | : Cross-flow heat exchanger |
| $min$ | : Minimum |
| $max$ | : Maximum |
| $f$ | : Fresh |
| $w$ | : Waste |
| $\infty$ | : Infinite |
| $wl$ | : Wall |
| $fl$ | : Fluid |
| $I$ | : Inlet |
| $o$ | : Outlet |

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# PROCEEDING

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