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Experimental Investigation of an Air to Air Heat Pipe Heat Exchanger for Moderate Temperature Waste Heat Recovery

Saddam Hossen[*], *Mahmud-Or-Rashid, Mantaka Taimullah, Farhan Ahmed Shakil, and Dr.A K M Monjur Morshed*
Department of Mechanical Engineering, Bangladesh University of Engineering & Technology, Dhaka-1000, BANGLADESH

ABSTRACT

Due to environmental concern and high price of the fuel, waste heat recovery has become a central issue for industrial and commercial energy users. Heat pipe heat exchanger (HPHE) could be employed in this regard economically. In this study, an HPHE consisting of heat pipes arranged in stages has been developed. Water was used as the heat carrying fluid inside the heat pipe and square fins were used in the cooling and heating zone of the heat pipe. The constructed HPHE was placed between two ducts carrying hot and cold air. The hot fluid temperature was varied from 60 to 80°C which resembles waste heat and cold air was atmospheric air. The hot and cold air's mass flow rate was varied between 0.037 and 0.087 kg/s and heat transfer between two air streams were measured as 228.5 to 362.2W and heat transfer coefficient varies from 4.22 to 8.09 W/m^2-K.

Keywords: Heat pipe, Heat pipe heat exchanger, Air to air heat exchanger, Waste heat recovery

1. Introduction

Energy is the key element in modern life and at the same time is responsible for environmental pollution and global warming. To keep pace with modern life and at the same time to reduce environmental footprints, efficient utilization of the energy resources has become a key concern. A large amount of energy is being wasted while converting the energy into useful work. At present, about 20% to 50% of energy used in the industry is rejected as waste heat [1]. Recovering the waste heat from the industrial processes is one of the ways to reduce energy consumption without hampering the quality of the processes. With the increase of fuel price and environmental concern, waste energy recovery is becoming popular. Waste heat from processes comes in both high quality energy, where the temperature varies between 220°C and 700°C (e.g. generator exhaust, boiler exhaust, reheating furnace exhaust, etc.) and low quality energy, where the temperature is less than 100°C (e.g. compressed air cooling, stenter machine exhaust, bakery dryer, HVAC system, etc.). Waste heat recovery system and technology is well established for the high quality waste energy sources whereas for the low grade waste energy sources, heat recovery is not popular due to technological and economical limitations.

To recover the waste heat from the low temperature sources, heat pipe heat exchanger (HPHE) is an efficient way [1-10], where heat can be extracted at a very low temperature difference. Heat pipe is a known technology. The idea of heat pipe was first presented by Gaugler in General Motor Company in 1942. The first heat pipe was designed and manufactured by Grover in National Lab, Los Alamos, in the US in 1964 [1]. Since then, heat pipes are being used in many applications such as, heat exchangers (air pre-heaters or systems that use in economizers for waste heat recovery), HVAC system, cooling of electronic components, solar energy conversion systems, spacecraft thermal control, cooling of gas turbine rotor blades etc. In recent days, some common applications of HPHE are in medicine and human body temperature control [2], spacecraft cooling [3], electrical and electronics equipment cooling [4, 5], waste heat recovery applications [6-11] etc.

In a heat pipe heat exchanger (HPHE), a group of vertical heat pipes is arranged in such a manner that two streams of fluid can flow over them through two separate ducts or pipelines. A high temperature fluid flows on one end of the HPHE (known as evaporation section) and a low temperature fluid flows on the other end (known as condensation section), thereby transfers heat from the high temperature fluid to the low temperature one using the fluid sealed in heat pipes as heat carrier. The heat pipes in a heat pipe heat exchanger are arranged in stages, each stage consisting of a single row of heat pipes, all of which are at the same temperature. Hagens et al. [12] studied experimentally the heat exchanger consisting of heat pipes with two different filling ratios of R-134a: 19% and 59% which demonstrated that a heat pipe heat exchanger is a good alternative for air–air exchangers in process conditions when air–water cooling is not possible. S.H Noie-Baghban and Majideian [13] studied experimentally the performance of distilled water filled heat pipe equipped heat exchanger at low temperatures (15-55°C) and concluded that appropriate method of vacuum, filling ratio and sealing of the heat pipe are necessary for increasing the effectiveness of heat pipe heat exchanger. Nguyen-Chi et al. [14] investigated experimentally the performance of vertical two-phase close thermosiphon and used water as a working fluid. They investigated the influence of operating parameters on the maximum performance either by dry out or burn out limits. Li et al. [15] investigated experimentally the steady-state heat transfer characteristics of a vertical two-phase closed thermosiphon at low temperature differences with R-11, R-22 and water as working fluids. Park and Lee [16] made an experimental study on the performance of stationary two-phase closed thermosiphon with three working fluid mixtures (water–glycerin, water-ethanol, and water–ethylene glycol).

[*] Corresponding author. Tel.: +88-01
E-mail addresses: saddamme170@gmail.com

Shiraishi et al. [17] investigated experimentally a critical heat transfer rate in thermosiphons by taking into account the aspect ratio, filling ratio, working fluid property, and operating pressure.

In this paper, a vertical heat pipe (thermosiphon) heat exchanger is designed to recover heat from low temperature region (from 55^{o}C air to ambient temperature air). The design of the HPHE is presented and the results for experimental investigations are reported. The performance of the HPHE is evaluated by varying the filling ratio of the heat pipes and mass flow rates of hot and cold air for an optimum operating condition thus optimizing the effectiveness of the HPHE.

2. Experimental apparatus and procedure

To investigate the heat transfer performance and evaluate the effectiveness of a HPHE and also to determine the optimum filling ratio and operating conditions of HPHE system for low temperature waste heat recovery application, an experimental setup was designed and constructed. The test system consisted of a HPHE, a data collection system, two fans for cold and hot air passing, an air pre-heater, four k-type thermocouples etc. as showing in the figure: 1 (a), (b), (c) and (d). In this study the designed HPHE was consisting of thirty eight heat pipes that are arranged vertically on the separation plate with two different rows and in seven columns, where 1st row consists of five tubes and 2nd row consists of 6 tubes total (5+6+5+6+5+6+5) = 38 tubes. Tubes are arranged in triangular formation for creating the turbulent flow in both condensation and evaporation section. Each heat pipes consists of a seven square fins (1.5 ×1.5 inch) of copper plate. Fins are arranged in the heat pipes in such way that, the flow becomes zigzag and create more turbulence and thus increase the heat transfer rate.

The working fluid selected for the heat pipes is water as it is cheap and has high latent heat of evaporation. Water is inserted into the copper pipe after sealing its one end, then it is heated up to its boiling point to make it air free and then the other end is sealed up .When the steam condense; vacuum is created by the vacuum inside the tube. The filling ratio of the working fluid (distilled water) in the heat pipe is varied form 33% and 50% of the heat pipe volume and then performance of the heat pipes were tested under those filling ratios. Thus an optimum filling ratio is obtained that ensures the maximum performance of heat pipe. The length of heat pipe 558 mm with inner and outer diameter of 13 and 15 mm. The lengths of the evaporator and condensation section in HPHE are 277 mm and 277 mm respectively.

Two ducts were arranged with the constructed HPHE in both condensation and evaporation section for passing the cold and hot air receptively with the help of two fans that are fitted at the two ends of the ducts. An air–preheater of 4500 W is used in the duct of evaporation side for heating the air. The temperature of air is controlled to 40°C to75°C by a temperature controller. The cold air in the condensation section is taken from the atmosphere.

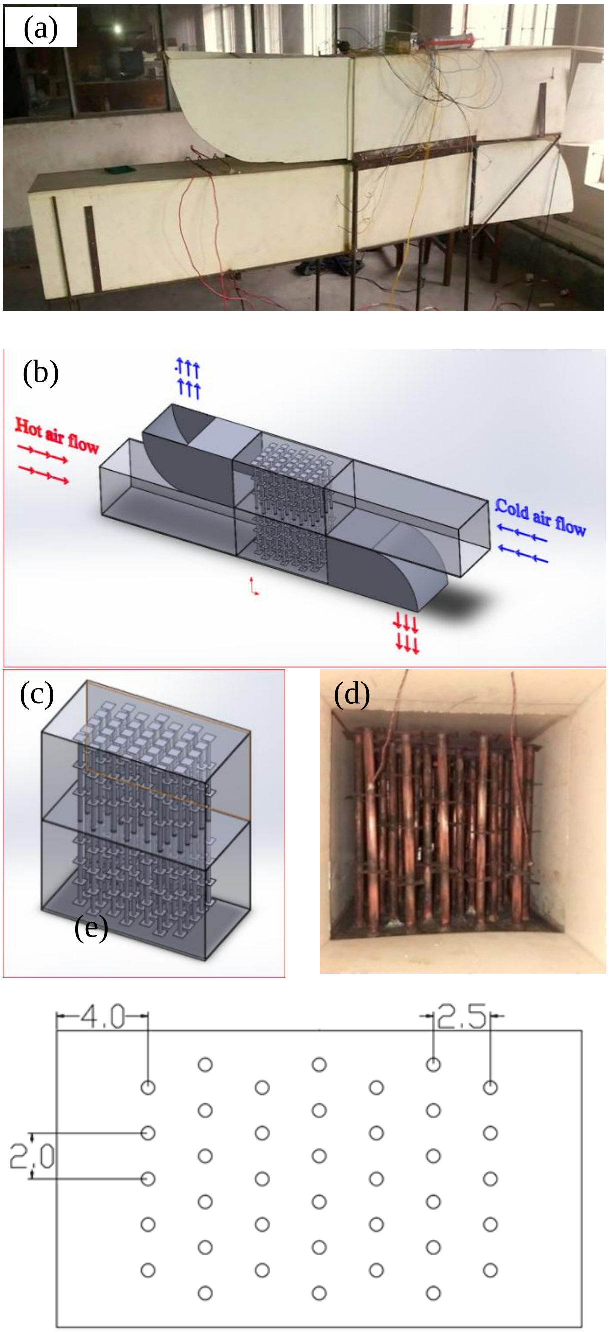

Fig.1 (a) Experimental setup; (b) Drawing for the experimental setup; (c) Drawing of the heat exchanger; (d) Front view of the heat exchanger; (e) Heat pipe arrangement.

For measuring the temperature of hot and cold air in condensation and evaporation inlet, outlets there are four k-type thermocouples were used. The mass flow rate of air is measured by anemometer.

Fig.2 Anemometer

3. Data reduction

The heat transfer rate for the HPHE from the hot flow air can be calculated by the following equation:

$$\dot{Q} = \dot{m}_{\mathrm{HA}} C_{pHA}(T_{HA,in} - T_{HA,out}) \qquad (1)$$

Where, $\dot{m}$is the mass flow rate of hot air, C_p is the specific heat capacity, $T_{HA,in}$and $T_{HA,out}$ refer to the inlet and outlet temperature of hot air respectively.

Similarly, $\dot{Q}$ can be also obtained by the cold air from the following formula,

$$\dot{Q} = \dot{m}_{\mathrm{CA}} C_{pCA}(T_{CA,in} - T_{CA,out}) \qquad (2)$$

This heat is not same to previously calculated heat transfer from the hot air due to uncertain heat loss.The overall heat transfer coefficient, U of the HPHE is defined as follows, W/ (m^2 K):

$$\mathrm{U} = \dot{Q} \,/\, A \,.\, \Delta T_{lm} \qquad (3)$$

Where, A is the overall heat transfer area of the HPHE,(m^2) and logarithmic mean temperature difference ΔT_{lm}, *(K)*, which is calculated for a counter-flow arrangement as follow:

$$\Delta \mathrm{T_{lm}} = \frac{(\mathrm{T_{HA,in}} - \mathrm{T_{CA,out}}) - (\mathrm{T_{HA,out}} - \mathrm{T_{CA,in}})}{\ln\left[\frac{(\mathrm{T_{HA,in}} - \mathrm{T_{CA,out}})}{(\mathrm{T_{HA,out}} - \mathrm{T_{CA,in}})}\right]} \qquad (4)$$

The effectiveness of HPHE is defined as the ratio of the actual heat transfer rate $\dot{Q}$ in a given heat exchanger to the maximum possible heat transfer rate $\dot{Q}_{max}$

$$\varepsilon = \dot{Q}/\dot{Q}_{\mathrm{max}} \qquad (5)$$

The following equation can be used to calculate the maximum theoretical heat transfer rate:

$$\dot{Q}_{max} = C_{min}(T_{HA,in} - T_{CA,in}) \qquad (6)$$

Where, $C_{min}$is the smaller one of the heat capacities of hot air (C_{HA}) and cold fresh air (C_{CA}), kJ/K. C_{HA} and C_{CA} are calculated by following relations:

$$C_{HA} = \dot{m}_{HA} C_{pHA} \qquad (7)$$

$$C_{CA} = \dot{m}_{CA} C_{pCA} \qquad (8)$$

$\mathrm{C_{max}}$ is the larger one of the hot (C_{HA}) and cold air (C_{CA}) specific heat capacities.R is the ratio of the minimum and maximum heat capacity of the two fluid streams:

$$R = C_{min} / C_{max} \qquad (9)$$

The number of heat transfer units (*NTU*), an important parameter for the heat exchanger, is expressed as follows:

$$NTU = UA \,/\, C_{min} \qquad (10)$$

Where, U is the overall heat transfer coefficient, A is heat transfer surface area.The *ε-NTU* method is a thermodynamic calculation method of dividing wall type of heat exchanger, which is derived by the dimensionless equation when the logarithmic mean temperature difference is discussed. The relationship between ε and *NTU*canbe expressed by:

$$\mathcal{E} = \frac{1 - \exp[-1(1 - \mathrm{R})\mathrm{NTU}]}{1 - \mathrm{R} \cdot \exp[-(1 -)\mathrm{NTU}]} \qquad (11)$$

4. Results and discussions

4.1 Performance of the Heat Pipe

In this experiment water is selected as working fluid because of its availability, low cost and also depending on its performance. Tests were performed and performances of a water filled heat pipe, an ethanol filled heat pipe and an empty copper tube were compared. The performance results reveal that water filled heat pipe shows better heat transfer performance over the other two. The test results are presented the following figures.

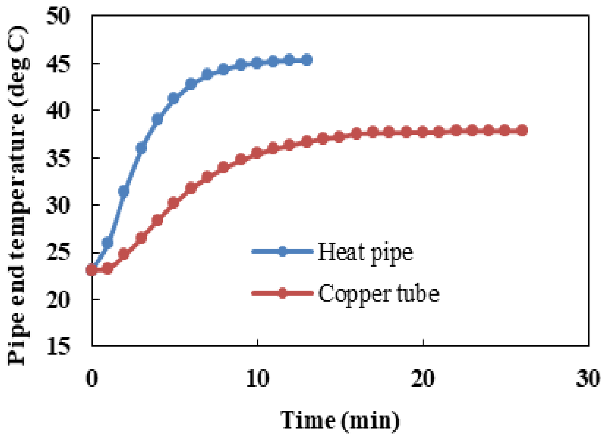

Fig.3 Variation of pipe end temperature with time when pipes other ends inserted into water initially at 57 °C

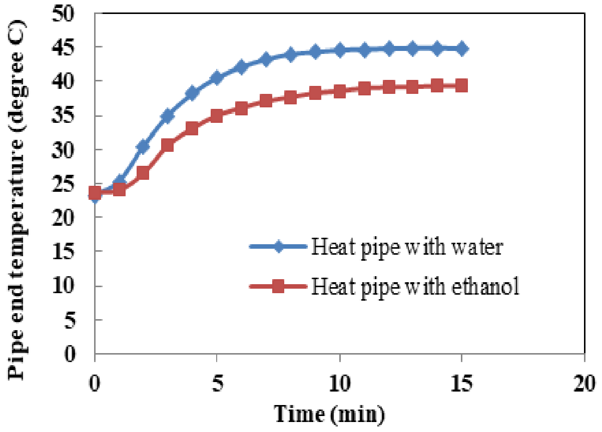

Fig. 4 Variation of pipe end temperature with time when pipes' other ends inserted into water initially at 53°C

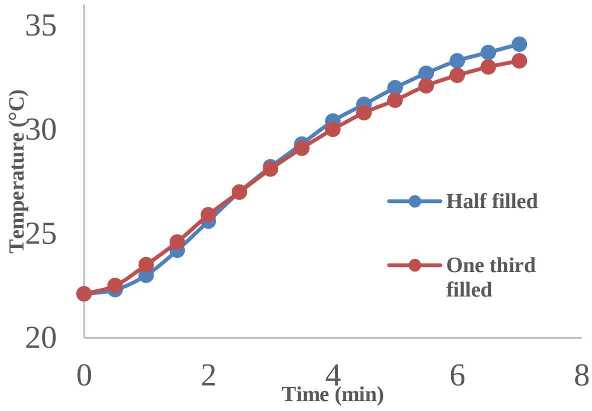

Fig.5 Variation of heat pipe performance with filling ratio

The filling ratio has a significant effect on the performance of the HPHE. For analyzing the performance of heat pipe by varying the filling ratio, a heat pipe is selected which length is 568 mm with 15 mm outer diameter and 1mm thickness.Working fluid was filled to 50% and 33% of total heat pipe volume for the performance test. The performance results are expressed with respect to the increase of top end temperature of heat pipe with time. In the initial period, the one-third filled heat pipe showed better performance than the half-filled heat pipe. But after a certain period of time, the situation had reversed. The half-filled heat pipe showed better performance than the one-third filled heat pipe. So in this experiment 50% filling ratio is taken as optimal filling ratio, then all heat pipes are constructed and assembled for HPHE.

4.2 Analysis on the performance of the HPHE

The variations of heat transfer rate,overall heat transfer co-efficient and effectivenesswith hot air mass flow rates at different cold air mass flow rates are presented in Fig. 6, Fig.7 and Fig. 8. From the results, it is clear that both the heat transfer rate and overall heat transfer coefficient increase with the increase of hot and cold air mass flow rates and effectiveness decrease.

In the experiment, the heat transfer rate changes between 228.5 and 1003.4 W and the overall heat transfer coefficient varies between 4.22 and 13.88 W/m^2-K. The heat transfer rate and overall heat transfer coefficient gets the minimal value, when the hot air mass flow rate is 0.034 kg/s, maximum values when the hot air flow rate is 0.124 kg/s. The pattern is nearly similar for comparison with cold air mass flow rate also. The heat transfer coefficient is very low when the air flow rate is small. There are several reasons behind this phenomenon. One of the main causes is the turbulence. When the air flow rate is small, laminar flow is predominant and under laminar flow condition heat transfer coefficient is small because of lack of mixing of the fluid. When flow rate is high, turbulence is created and proper mixing takes place and thus heat transfer coefficient is also increased. The same reason is for the variation of heat transfer rate. So heat transfer can be increased by increasing the air flow rate.

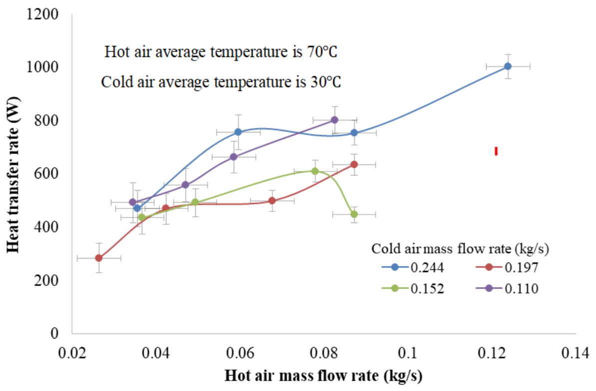

Fig.6 Effect of hot air and cold air mass flow rates onheat transfer rate.

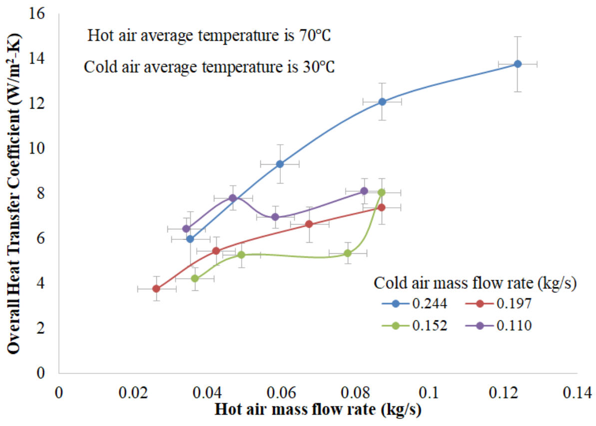

Fig.7 Effect of hot air and cold air mass flow rates on overall heat transfer coefficient.

The relationship between effectiveness and mass flow rate was different from previous patterns. Here effectiveness decreased with increasing of hot air mass flow rates at a constant cold air mass flow rate. It was summarized from analyzing data of an experiment that for cold air mass flow rate 0.244 kg/s, effectiveness was decreased from 0.19 to 0.13 when hot air mass flow rate increased from 0.04 to 0.124 kg/s. So it was concluded that this HPHE was more effective and suitable for lower mass flow rate.

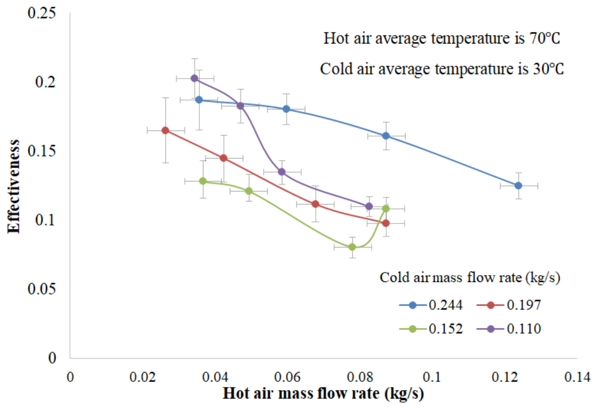

Fig.8 Effect of hot air and cold air mass flow rates on effectiveness of HPHE.

In this paper, the effectiveness-NTU method regarding heat exchanger operation has been applied, and the nature of the relationship between effectiveness and NTU at different air mass flow rates is shown in Fig 9. From the figure, it is clear that that the effectiveness of HPHE increases with the increasing of NTU and the pattern of the relationship between effectiveness and NTU is nearly linear. It is because NTU is directly proportional with heat transfer coefficient and as heat transfer co-efficient increases with increasing air mass flow rates, NTU is also increased and when NTU increases effectiveness of HPHE also increases as the nature of their relationship described in theory. Here the effectiveness varying from 0.08 to 0.202, and the relationship can be expressed as **ε = 0.8183 NTU + 0.008** from the best fit straight line.

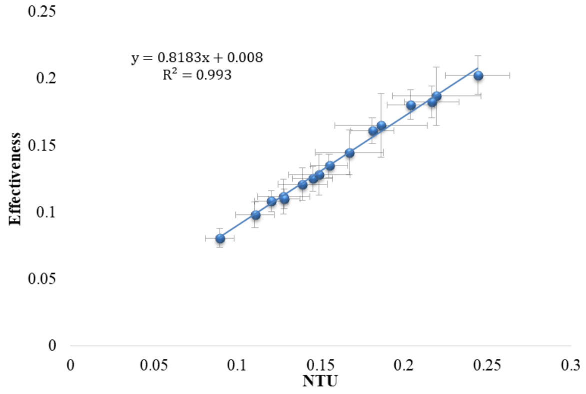

Fig.9 Relationship between effectiveness and NTU

5. Conclusions

In this study, experimental work was carried out to investigate the effectiveness of a low cost HPHE in recovering low grade waste heat. From the results of the experimental investigation following conclusions can be drawn:

1. Low cost HPHE can be constructed without any sophisticated equipment at laboratory with water as the working fluid.
2. The performance of heat pipe in steady stateis better for half-filled heat pipe than one-third filled heat pipe.
3. The heat transfer rate and overall heat transfer co-efficient increases with increasing mass flow rate of air butthe effectiveness of the HPHE decreases.
4. The relation between effectiveness and NTU is linear, where the effectiveness varying from 0.08 to 0.202. The relationship can be expressed as **ε** = 0.8183 NTU + 0.008.
5. The heat exchanger is very sensitive to the dust accumulation and automatic cleaning of the heat exchanger would be necessary to get the maximum performance.

NOMENCLATURE

WHRS	waste heat recovery system
HPHE	heat pipe heat exchanger
NTU	number of heat transfer units
HVAC	heating, ventilation and air conditioning.
WHRS	waste heat recovery system
$\dot{Q}$	heat transfer rate (kW)
$\dot{m}$	mass flow rate (kg/h)
$\dot{m}_{HA}$	hot air mass flow rate (kg/h)
$\dot{m}_{CA}$	cold air mass flow rate (kg/h)
C_p	specific heat (kJ/(kg K))
C_{pHA}	specific heat of hot air (kJ/(kg K))
C_{pCA}	specific heat of cold air (kJ/(kg K))
T	temperature (K)
$T_{HA,in}$	inlet temperature of hot air (K)
$T_{HA,out}$	outlet temperature of hot air (K)
$T_{CA,in}$	inlet temperature of cold air (K)
$T_{CA,out}$	outlet temperature of cold air (K)
U	overall heat transfer coefficient (W/(m^{2}K))
A	overall heat transfer surface area (m^2)
ΔT_{lm}	logarithmic temperature difference (K)
C	heat capacity (kJ/K)
C_{HA}	heat capacity of hot air (kJ/K)
C_{CA}	heat capacity of cold air (kJ/K)
ε	heat exchanger effectiveness
$\mathrm{C_{min}}$	Minimum heat Capacity(kJ/K)
$\mathrm{C_{max}}$	Maximum Heat capacity(kJ/K)

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