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Experimental research on a novel porous ceramic tube type indirect evaporative cooler

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Abstract

Traditional indirect evaporative coolers (IEC) made of metal foil or polymer suffer from poor surface hydrophilicity in the wet channels and large amount of continuously circulated water. To solve the two problems, a kind of novel porous ceramics material was proposed for manufacturing the IEC in this paper for its high hydrophilicity and water storage features. The high hydrophilic property can improve the cooler's efficiency by increasing the heat and mass transfer area and the water storage behavior enables intermittent water supply so as to reduce the energy consumption and to save water. A porous ceramics tube type IEC was designed, fabricated and tested. The influences of secondary air to primary air ratio and water spray rate were studied. Dynamic performance of the IEC was tested in a typical day of Xi'An, China. Besides, comparisons were made between the novel IEC and other IECs. Experimental results show that the cooling efficiency of the IEC remains stable

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for 100 minutes after the tube is fully wetted under a continuous water spray of 150L/h for 5 minutes. The novel IEC saves 95% of the pump energy consumption compared with traditional one and the highest COP is 34.9.

Keywords: porous ceramics; tube type; indirect evaporative cooler; energy saving; intermittent spray

1. Introduction

Evaporative air conditioning technology is an energy saving and environmental friendly natural cooling technology which has been widely recognized by industrial community and applied in many practical projects [1~3]. It uses the difference between the dry-bulb temperature and wet-bulb temperature of ambient air as driven force in water evaporation process. The process converts the sensible heat into the latent heat so that the air is cooled. Indirect evaporative cooler (IEC) consists of multiple alternative dry channels and wet channels separated by metal or polymer walls. The circulation water is sprayed into the wet channels to form a layer of water film covered on the wall. The secondary air flows over the water film and the wall temperature is lowered when water evaporates. Simultaneously, the primary air in the adjacent dry channels is sensibly cooled [4,5].

The traditional IEC is made of metal foil or polymer [6]. The aluminum is the most commonly used metal for making IEC because it has good thermal conductivity and is easy for manufacturing. The polymer is used for manufacturing IEC at the very beginning. Although its thermal conductivity is worse than the metal, it has advantages like durable and corrosion-resistant [7]. However, both of the materials suffer from poor surface hydrophilicity in the wet channels and large amount of continuously circulated water. Fibre is another popular material for marking IEC in recent years. It is cheap and porous but the thermal conductivity is low. It is reported by Qiu [8] that the wettability ratio of the IEC walls is only 1/3 to 2/3 under real operation. Thus, the wet-bulb efficiency is always much lower than the rated value given by the product specifications. In addition, limited to the property of traditional material, the water has to be sprayed continuously to enable the complete water film, which results in large amount of circulated water and high energy consumption of the pump. Thus, some improvement measures were proposed and novel materials were used to improve the IEC performance.

Zhao et al. [9] compared several possible types of material (metals, fibers, ceramics, zeolite and carbon) for making IEC in terms of thermal conductivity, porosity, shaping ability, compatibility with coating, contamination risk and cost. The wick attained aluminum was pointed out to be the most adequate structure/material. Xu et al. [10] experimentally tested a range of fabrics (textiles) and found most of them have superior properties in moisture wicking ability, diffusivity and evaporation ability. Similarity, Huang et al. [11] experimentally investigated the improvement of IEC wet-bulb efficiency by using a water-absorbing textile material covered on the aluminum foil tube walls. The results show that the wet-bulb efficiency can be improved by 20% to 30% compared with naked aluminum tubes. However, using textile material could bring the problems of rotting and bacterial growth. Regular replacement of textile absorber improves the maintenance and management costs. Fan

[12,13] made a preliminary study to improve the hydrophilic and antibacterial performance of the IEC. Three methods were put forwarded, including using hydrophilic heat exchanger, adopting nanometer photochemical catalysis technology and coating hydrophilic fibers on the tubes. The fibers performs better as it has good water permeability that allows water to spread across the wet surface. However, the main shortcoming of the fiber is the low thermal conductivity.

The performance of IEC is affected by many factors, such as the inlet air temperature and humidity, spraying water density, secondary/primary air ratio and material property and structure [14,15]. The influence of each the above factor is widely studied experimentally and theoretically [16~19]. However, majority of the relative conclusions are drawn based on traditional materials or assuming the wettability ratio equals to one. The porous ceramics, as a novel material for making the IEC, has not been experimentally studied in open literature. Its unique hydrophilicity and water storage features could bring different influences to IEC operation characters, which is worth deep investigating.

To solve problems of the poor surface hydrophilicity of IEC and large energy consumption of continuous-working pump, a kind of novel porous ceramics material was proposed for manufacturing the IEC in this paper. It has high porosity, small volume density, large specific surface area and high thermal conductivity. The porosity and capillary action of porous ceramic tube can fundamentally improve surface hydrophilicity and enlarge the heat and mass transfer area compared with the traditional IEC. It can be also served as water storage device, which substitutes the continuous spraying of the pump by intermittent water supply so as to reduce the energy consumption, save the water and improve the overall efficiency of IEC.

This paper experimentally studies the performance of the novel porous ceramics tube type IEC. An example IEC is fabricated and tested under various operating conditions. The influence of secondary to primary air ratio and spraying water flow rate are studied and optimal values are given as useful application guidance. The intermittent water spray is also proposed for high-efficient operation of the porous ceramics IEC.

2. Experimental test rig

2.1 Porous ceramics tube type indirect evaporative cooler

Porous ceramics is suitable for IEC for the advantages like high porosity, large specific surface area, high water storage capacity, high thermal conductivity, corrosion-resistance, durability and capillary effect. Considering the current ceramic materials, through-hole type corundum with pore diameter of 60~ 65μm is selected to be used for making IEC. The inner wall of the pipe is coated with a layer of water insulation porous ceramic membrane to ensure the water does not penetrate to the dry channels. The porous ceramic can be treated as aqueous non-absorbent porous material when the IEC works. There are three characteristics of aqueous porous ceramic tube. Firstly, water is present in the voids of porous ceramics in the form of free water. The whole porous ceramic is considered as a network consisting of many capillary structures with different diameter. Secondly, there are a large number of multi-phase interfaces including water-solid, water-gas and solid-gas interface in the voids of porous ceramics. Thirdly, there are at least two gases including water vapor and air in the gas phase space. These characteristics determine the complex heat and mass transfer process inside IEC.

The structure of the investigated IEC is shown in Fig. 1. The diameter for each porous ceramic tube is Φ30×5 and length is 0.6m. The impermeable ceramic membrane is adopted for the tube inner surface. There are 7 rows of tubes vertically arranged in staggered pattern. Seven tubes for odd rows and six tubes for even rows, which gives a total number of 46 tubes. The spacing between horizontal and vertical tube is 40mm. The windward area for primary air is 290mm×290mm and secondary air is 290mm×600mm. The total heat transfer area is calculated to be 2.60m^2. The porous ceramic tubes are assembled together to form a packaged IEC after all the tubes complete processing. The flanges are reserved for the inlet and outlet of primary and secondary air. In the end, good seal is provided to joint the porous ceramic tubes and galvanized steel plate box. The physical graphs of porous ceramics tube type IEC are shown in Fig. 2.

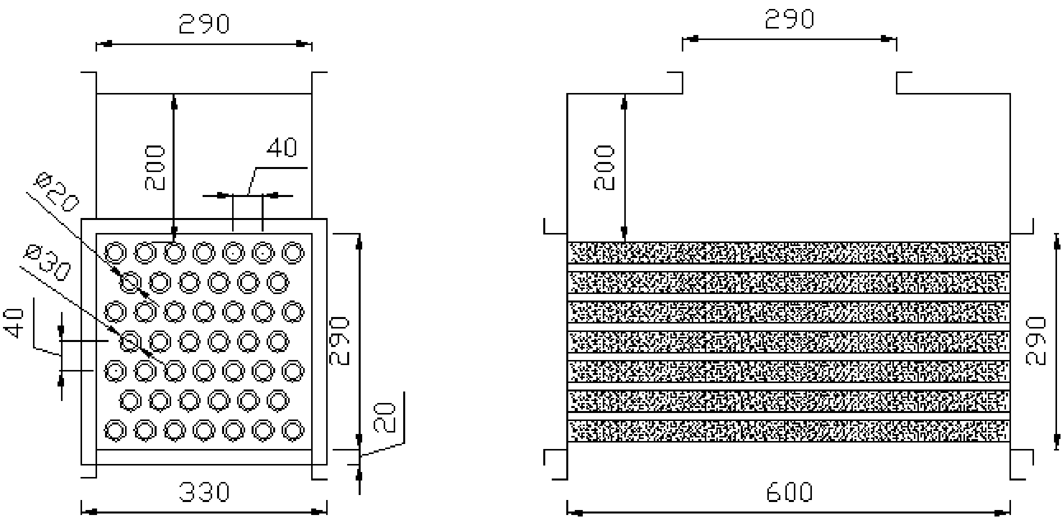


Fig. 1 Structure diagram of porous ceramics tube type IEC

(a) porous ceramics tube

(b) packaged unit

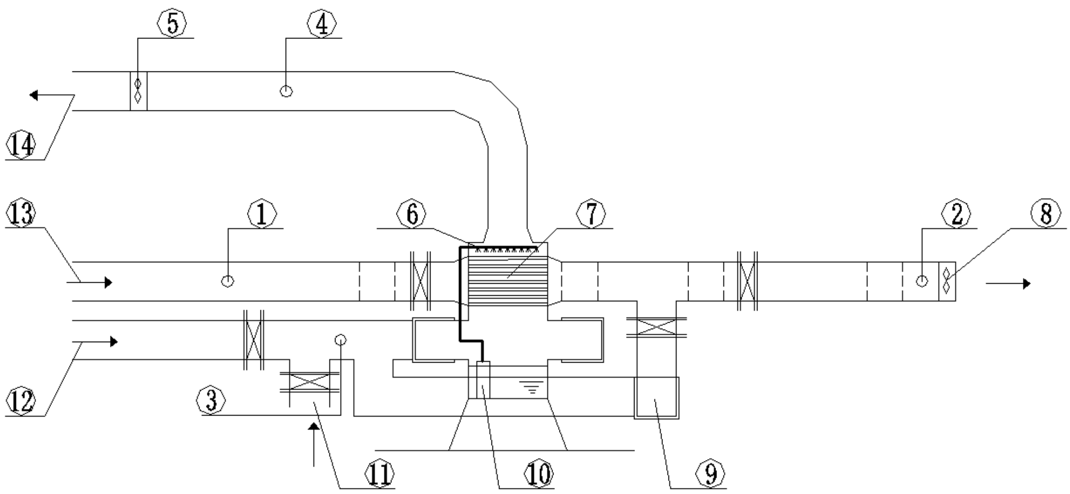
Fig.2 Real photos of porous ceramics tube type IEC

2.2 Test bench

2.2.1 Schematic diagram and measuring parameters

The IEC efficiency and temperature drop are great influenced by the temperature and humidity of secondary air. Three kinds of secondary air were used in the experiment, including the outdoor air, indoor return air and primary air after treatment by IEC. Accordingly, the pipeline is designed to provide the three kinds of air supply. The inlet and outlet air conditions were measured separately. The schematic diagram of the test rig is shown in Fig. 3.

Four measuring points were arranged in this experiment, namely inlet and outlet of the primary air from IEC and inlet and outlet of the secondary air from IEC. The collected operating parameters of IEC include the dry bulb temperature, relative humidity and air velocity of primary air and secondary air, and total pressure and static pressure of primary air. The test parameters, locations and instruments as listed in Table 1. The specifications of different measuring instruments are listed in Table 2.



① measure point of primary air inlet ($t_{p,in}$, $t_{wb,p,in}$, v_p, P) ② measure point of primary air outlet ($t_{p,out}$, $t_{wb,p,out}$, v_p, P) ③ measure point of secondary air inlet ($t_{s,in}$, $t_{wb,s,in}$, v_s, P) ④ measure point of secondary air outlet ($t_{s,out}$, $t_{wb,s,out}$, v_s, P) ⑤ secondary fan ⑥ sprayer ⑦ porous ceramic tube ⑧ primary air fan ⑨ outlet primary air used as secondary air ⑩ water pump ⑪ indoor return air used as secondary air ⑫ outdoor air used as secondary air ⑬ primary air inlet ⑭ secondary air outlet

Fig. 3 Schematic diagram of the test bench

Table 1 Test parameters, locations and instruments

Measuring points	Measuring location	The test content	Test instrument
①	Primary air inlet of IEC	Dry bulb temperature, relative humidity, air velocity, total pressure, static pressure	RHLOG-T-H temperature and humidity recording meter, SwemaAir300 airflow multifunction tester, DP-2000 digital pressure gauge, pitot tube
②	Primary air outlet of IEC		
③	Secondary air inlet of IEC	Dry bulb temperature, relative humidity, air velocity	RHLOG-T-H temperature and humidity recording meter, SwemaAir300 airflow multifunction tester
④	Secondary air outlet of IEC		

Table 2 Specifications of different measuring instruments

Parameters	Device	Range	Accuracy
Air dry bulb temperature	RHLOG-T-H	-25~55℃	±0.3℃
Air relative humidity	RHLOG-T-H	15~85% RH	±3% RH
Air velocity	SwemaAir300	0.1~30 m/s	±0.1m/s

The wet bulb efficiency is used for evaluating the cooling efficiency of IEC which is expressed as follows:

$$\eta_{wb} = (t_{p,in} - t_{p,out}) / (t_{p,in} - t_{wb,s,in}) \quad (1)$$

In the formula, $t_{p,in}$ is the dry bulb temperature of inlet primary air, ℃; $t_{p,out}$ is the dry bulb temperature of outlet primary air, ℃; $t_{wb,s,in}$ is the wet bulb temperature of inlet secondary air, ℃.

Fig. 4 Real photos of the test rig

2.2.2 Air duct size and fan specification

The dimension of the air duct is designed to be 250mm×250mm according to the cooler size and designed air velocity. The dimension of the primary air inlet and outlet and secondary air outlet is 290mm×290mm. The primary air inlet is connected with the air duct by gradually expanding duct. The primary air outlet and secondary air outlet are connected with the air ducts by tapered duct.

The designed primary air flow rate is 500 m^3/h and secondary air flow rate is 350 m^3/h. Considering the resistances brought by the measuring devices, valves and IEC, the capacity of the fans are over-size chosen in the test rig. The rated flow rate of the primary air fan (model: DF2G-2, axial fan) is 2380m^3/h and total pressure is 218Pa. The rated flow rate of the secondary air fan (model: DF2G-2, axial fan) is 1380m^3/h and total pressure is 148Pa. The air flow rate is adjusted by using a potentiometer during experiment.

2.2.2 Water spray and distribution system

Water spray system consists of water tank, water pump, rotor flowmeter, regulating valve, spray water pipe, refraction sprayers and water pump timer, as shown in Fig.5 and Fig.6. Submersible pump (model: QDX-0.37, power: 370W) with the rated flow rate of 1.5m^3/h and head of 16 meters is selected for water distribution. In order to determine the optimal drench water flow rate of the porous ceramic tube type IEC, a valve is added to regulate the flow rate and a rotor flow meter is used for data collection. Eight simple refraction sprayers are adopted with good wetting effect. The arrangement of the sprayers is shown in Fig.7. Because of good water storage capacity of the porous ceramic tube, the evaporation proceeds for a period of time even though the pump is turned off. In order to optimal the operation of pump, a pump timer is set up to control the on/off state of the pump at setting time intervals.

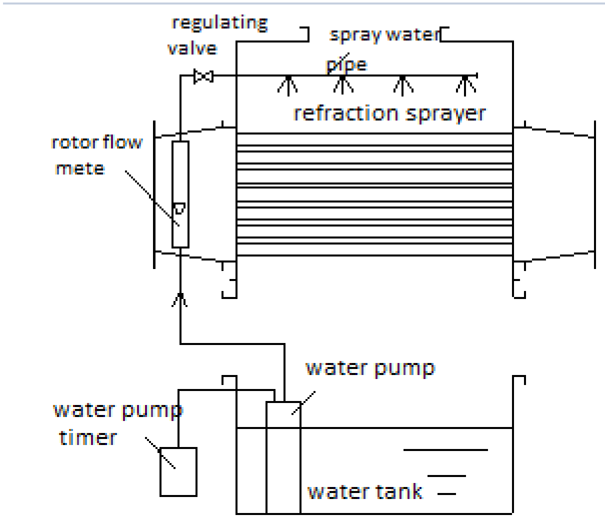


Fig.5 Diagram of spray water system

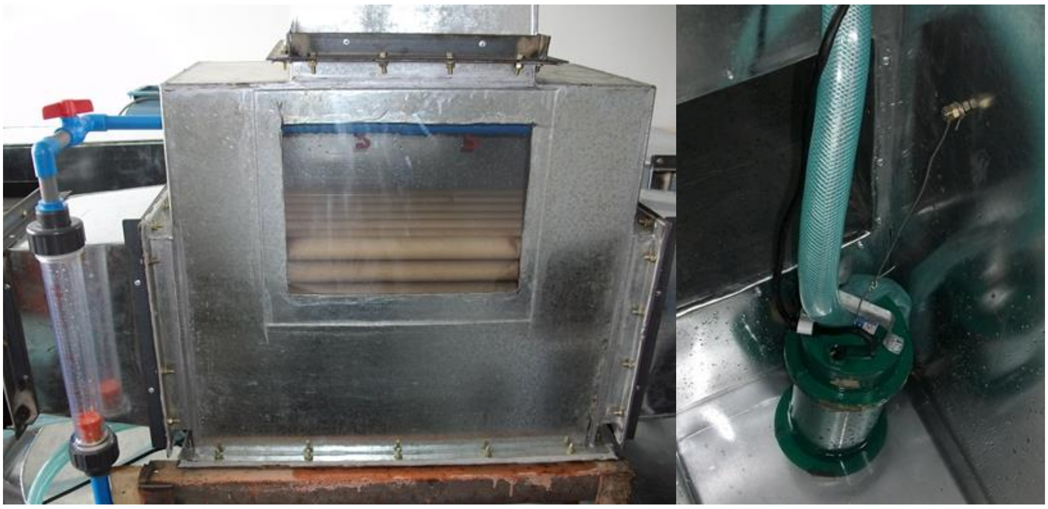


Fig.6 Real photos of spray water system.

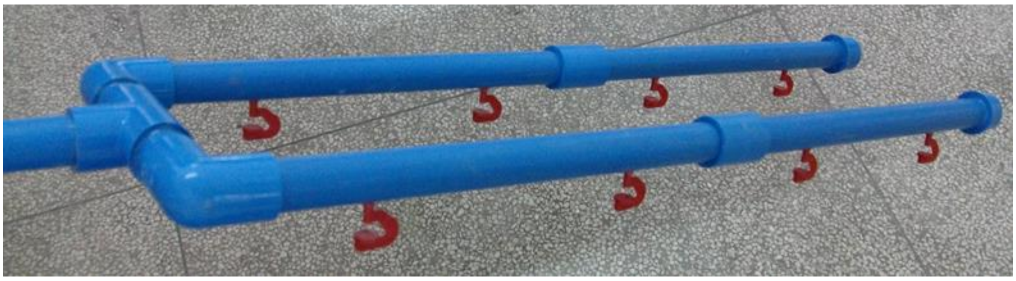


Fig.7 Real photos of sprayers' arrangement

2.3 Test plan

During the test, the potentiometer is used to adjust the air flow rate of the primary air and secondary air. The air flow rates are obtained by firstly dividing the whole cross section of duct into several equal areas and then calculating the average velocity by multiplying the air velocity and corresponding cross-sectional area ratio. In order to determine the optimal secondary/primary air ratio, four primary air flow rates are selected including 500m^3/h, 400m^3/h, 300m^3/h and 200m^3/h. The influence of secondary/primary air ratio on wet-bulb efficiency and temperature drop were investigated under the above four primary air flow rates. The air flow ratios are set to be 0.5, 0.6, 0.7, 0.8, 0.9, 1.0 and 1.1.

In order to determine the optimal drench water flow rate, the drench water flow rate changes under the optimal secondary/primary air ratio to observe the variation of the wet-bulb efficiency and temperature drop of IEC. Besides, the performance of IEC when the pump stops can also be obtained. All the air parameters data were recorded at 5 seconds step. The steady state is defined as the outlet temperature and relative humidity variations are within 0.1℃ and 1% for 5 minutes. The average values of the measured data in the 5 minutes span are used for steady operation analysis.

3. Results and discussion

3.1 Energy balance check and uncertainty analysis

The uncertainties of experimental results are caused by errors in the measuring process. The uncertainty analysis is conducted to examine the validity of collected data by measuring devices. The uncertainty analysis of all the measuring data in the experiment as well as the calculated performance indicators have been conducted using the method as follows. The function R is assumed to be calculated from a set of N measurements (independent variables), which is represented by:

$$R = (X_1, X_2, X_3, ..., X_N) \quad (4)$$

Then the uncertainty of the result R can be determined by combining uncertainties of individual terms using a root-sum square method:

$$\delta R = \sqrt{\sum_{i=0}^{N} (\frac{\partial R}{\partial x_i} x_i)^2} \quad (5)$$

where δR, x_i, δx_i are the total uncertainty associated with the dependent variable R, the independent variable which affects R, and the uncertainty of the variable x_i, respectively.

The uncertainty analysis results of different indicator is listed in Table 3.

Table 3 Uncertainty analysis results

Indicator	Nominal value	Relative uncertainty
Primary air flow rate V_p	500 m^3/h	± 3.7%
Secondary air flow rate V_s	450 m^3/h	± 4.3%
Wet-bulb efficiency η_{wb}	45%	± 5.8%
Heat transfer rate Q_{sen}	4003 W (wet)	± 5.8 % (wet)
	2626 W (dry)	± 9.3 % (dry)

To ensure the reliability of the test results, the energy balance of the test rig was checked. The enthalpy reduction of primary air should be equal to the enthalpy increase of secondary air based on energy balance theory. The energy conversation equations on primary air side and secondary air side are given as:

$$Q_p = m_p \cdot (i_{p,in} - i_{p,out}) \quad (2)$$

$$Q_s = m_s \cdot (i_{s,out} - i_{s,in}) \quad (3)$$

Fig.8 presents the comparison of enthalpy changes between the two air streams under both wet and dry operating conditions. The dry operating is without spraying water and wet operating is with spraying water. The discrepancies of all the experiment results are found to be within ±20%. Thus, the equipment is regarded as reliable for conducing the experiment.

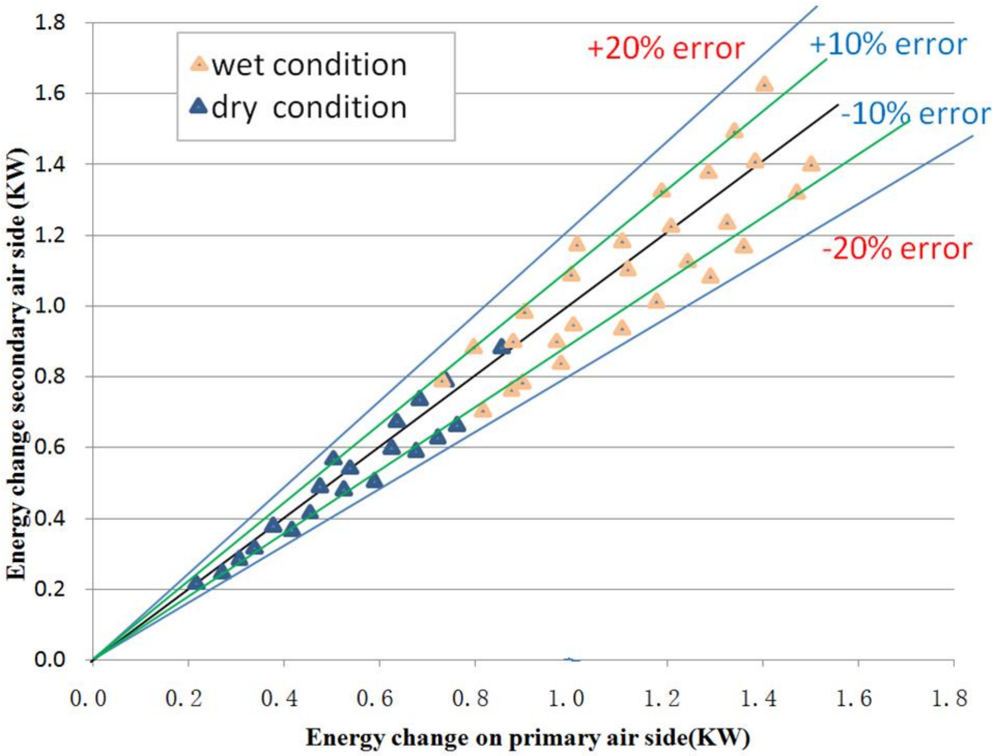


Fig.8 Energy balance of two air streams

3.2 Pressure drop

Fig. 9 shows the primary air pressure drop under different flow rate. It can be seen that the pressure drop increases from 7pa to 118pa with the increase of primary air flow rate from 100m^3/h to 500m^3/h. As the tube length is 600mm, the pressure drop per meter is calculated to be 155pa/m under the primary air velocity of 2m/s.

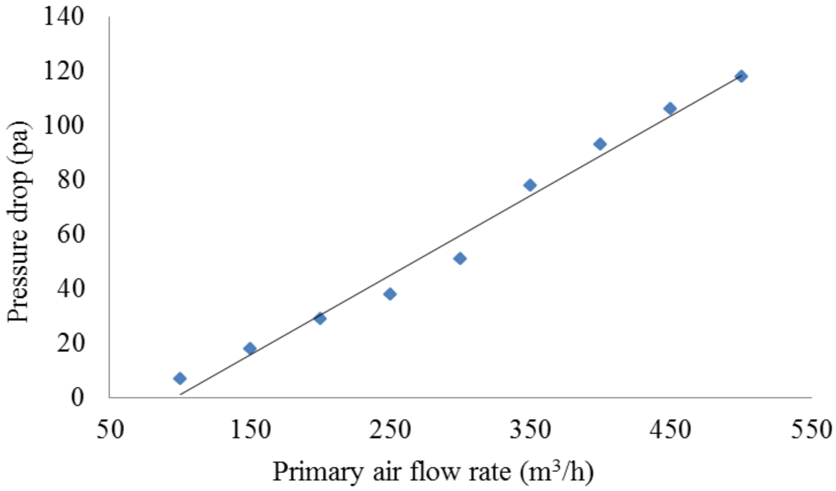


Fig.9 Pressure drop of primary air

3.3 Influence of secondary/primary air flow rate ratio and water spray rate

3.3.1 Influence of secondary/primary air flow rate ratio

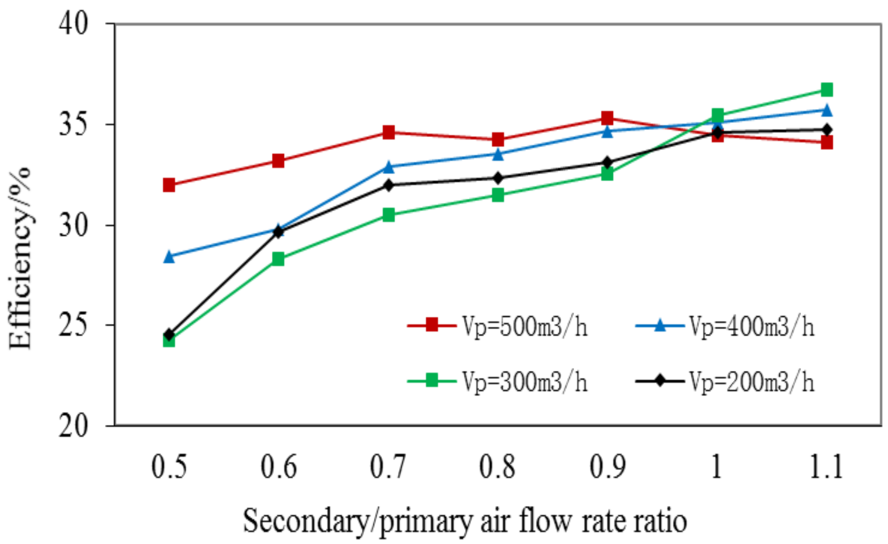


Fig.10 Influence of secondary/primary air ratio under various primary air flow rate.

The influence of secondary/primary air ratio under the primary air flow rate of 500 m^3/h, 400 m^3/h, 300 m^3/h and 200 m^3/h are shown in Fig.10. The performance indicators of IEC under different primary air flow rate are shown in Table 4. It can be seen from Fig.10 that the wet-bulb efficiency increases with the increase of secondary/primary air ratio for most of the cases. The maximum wet-bulb efficiency is about 34.8% to 36.7% when the flow rate ratio is 1.1. It is because the lower flow rate ratio results in less cooling media flow in the secondary air channels. In addition, the water film evaporation leads to humidity increase around the porous ceramic tube. If the secondary air velocity is too small, the high moist air can not be discharged to outside quickly so that the resistance increases in the heat and mass transfer process.

Table 4 Performance indicators of IEC under different primary air flow rate

Primary air flow rate (m^3/h)	Max efficiency	Average efficiency	Min efficiency
500	35.4%	34.0%	32.0%
400	35.7%	32.9%	28.4%,
300	36.7%	31.3%	24.3%,
200	34.8%	31.6%	24.6%,

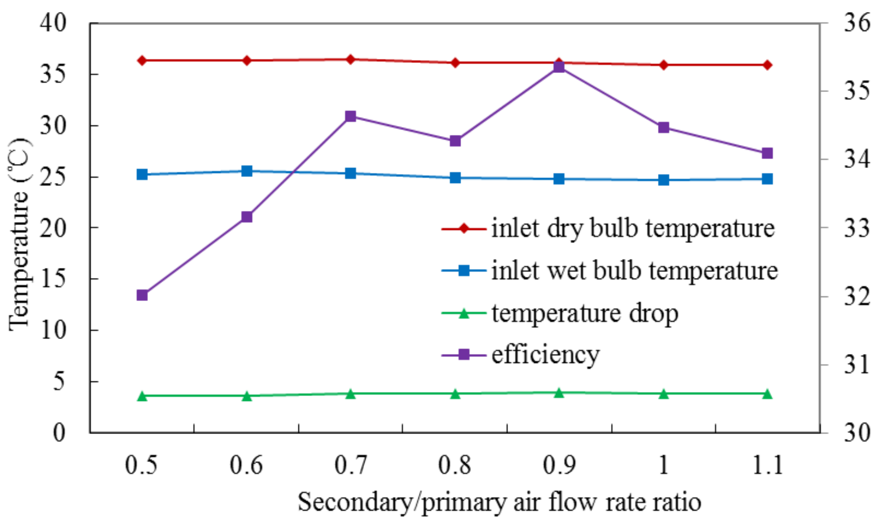


Fig.11 Influence of secondary/ primary air ratio on temperature drop and cooling efficiency (V_p=500m^3/h)

However, it is found that the optimal secondary/primary air ratio is 0.9 rather than 1.1 when the primary air flow rate is 500 m^3/h (u_p=9.6m/s). Fig.11 shows the variation of wet-bulb efficiency and primary air temperature drop under V_p=500m^3/h when secondary/primary air ratio ranges from 0.5 to 1.1. It can be seen from Fig.11 that the wet-bulb efficiency increases as the air flow rate ratio increases from 0.5 to 0.9 and then decreases a little when the air flow rate ratio keeps increasing from 0.9 to 1.1. It can be explained as follows. The moisture content of the secondary air outside the tubes would increase as the air flows across it and results in water evaporates. If the secondary air velocity is too small, the high humidity secondary air accumulated around the tubes can not be exhausted to outside. So the mass transfer resistance increases and results in lower efficiency. However, if the secondary air velocity is too large, the heat and mass transfer efficiency would be less sufficient because the limited contact time between water film and secondary air. Besides, the tiny water drops in the secondary air channels would be drawn into the exhaust air, which leads to worse wetting condition of the tube surface and water waste. In the experiment, it can be observed that there is water drops in the exhaust air when the secondary air flow rate increases to 500 m^3/h. In sum, the wet-bulb efficiency improves with the increase of secondary/primary air ratio only if the air velocity is in a certain range. The secondary air velocity should not be too large or too small when IEC operates to ensure the maximum heat and mass transfer.

3.3.2 Influence of water spray rate

The water spray rate has significate influence on the IEC performance according to the research findings from open literatures. Small water spray rate can result in insufficient wetting of tube surface while large water spray rate can lead to thick water film and energy waste. In order to determine the optimal water spray rate for the novel porous ceramic tube type IEC, a series of tests were conducted under different water spray rate and different primary air flow rate (500m^3/h, 400m^3/h and 300m^3/h). Under each test, the secondary/primary air ratio is set to be 0.9. The spray water flow rate varies from 250 L/h to 0 L/h continuously. The average wet-bulb efficiency and temperature drop were calculated under 10 minutes' steady operation condition. The influences of water spray rate on the wet-bulb efficiency and temperature drop are shown in Fig.12 and Fig.13, respectively.

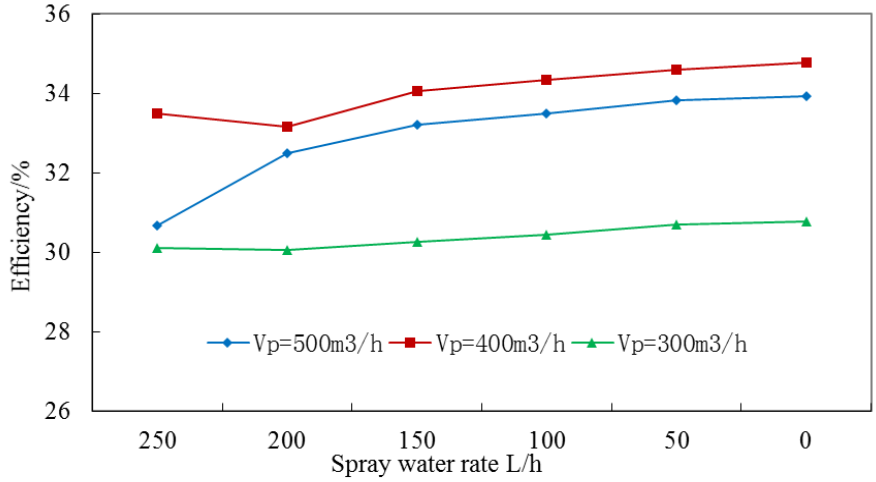


Fig. 12 Influence of spray water rate on IEC efficiency

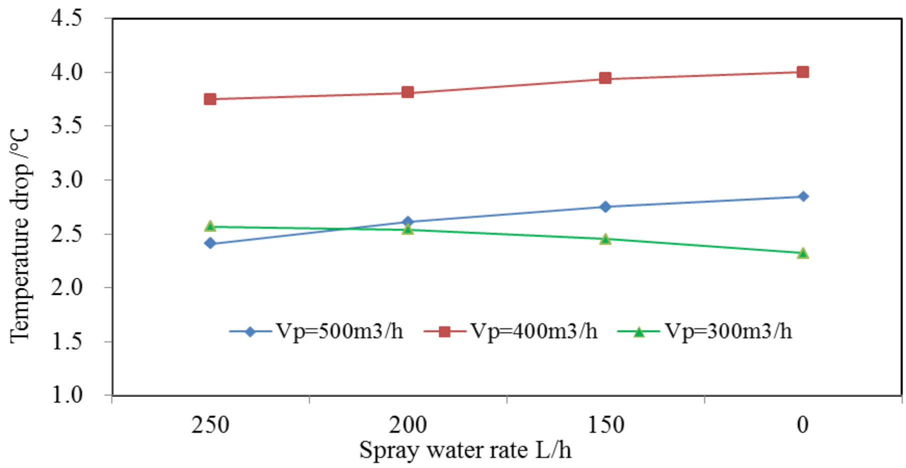


Fig. 13 Influence of spray water rate on temperature drop

It can be seen from Fig.12 and Fig.13 that the wet-bulb efficiency improves as the spray water rate decreases. It is surprised to find that the highest efficiency is achieved when the spray water flow rate is 0. It can be attributed to the special structure of the porous ceramic. Enough water is stored in the pores of the tube and permeates to the tube surface by capillary action. Thus, a thin evaporation water film forms even though spraying water stops for a period of time. According to the working principle of the IEC, it is the evenly distributed water film that enables the heat and mass transfer process in the wet channels. The larger the spray water flow rate would result in thicker water film and larger heat transfer resistance. Therefore, the wet-bulb efficiency decreases.

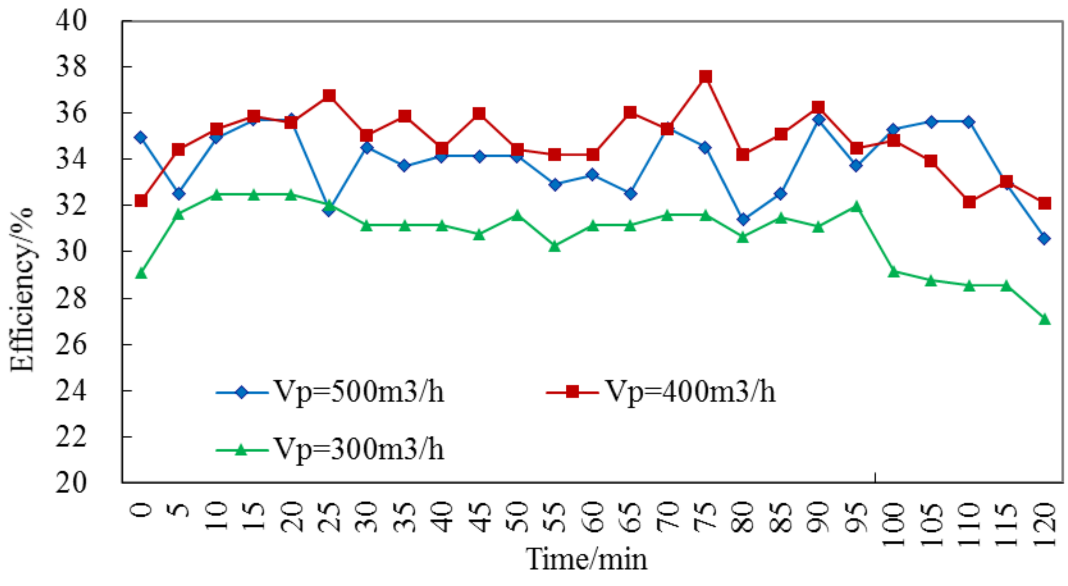


Fig. 14 Wet-bulb efficiency variation when the spray water flow rate changes from 150 L/h to 0 L/h

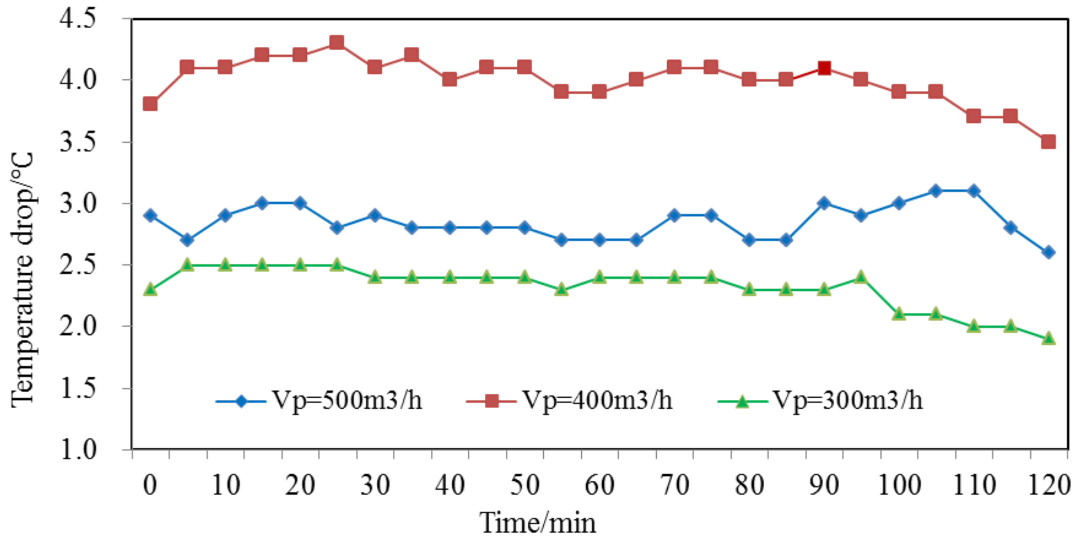


Fig. 15 Temperature drop variation when the spray water flow rate changes from 150 L/h to 0 L/h

Fig.14 and Fig.15 present the variation of wet-bulb efficiency and temperature drop in 120 minutes when the spray water flow rate changes from 150 L/h to 0 L/h. It can be seen that the efficiency and temperature drop remain at a relative steady level for the first 100 minutes although little fluctuation existed. The efficiency begins to decline gradually after 100 minutes. It proves that there is steady and evenly-distributed water retention on the tube surface inside IEC. Because of the water retention feature, the water film evaporation continues even though the water circulation stops. The capillary action keeps transporting the stored water in the pores to the surface of the tubes until the water is used up. In this way, the circulation pump can work intermittently so as to saving energy. Besides, it is expected that the thickness of the water film formed by capillary action would be thinner than the traditional water spray method.

Based on the test results, the spray water pump can intermittently operate for 5 minutes with the water flow rate of 150 L/h at 100 minutes interval. So the energy consumption of the pump is only 5% compared with that of the traditional IEC. Besides, the coefficient of performance (COP) of the IEC is calculated to be 24.4, 34.9 and 20.5 under the primary air flow rate of 500 m^3/h, 400 m^3/h and 300 m^3/h, respectively.

3.4 Dynamic performance under real operation condition

The dynamic performance of the novel porous ceramic IEC was also tested under real climate in Xi'an, a typical dry region in northwest China where evaporative cooling has good application potential. Fig.16 and Fig.17 show the wet-bulb efficiency and temperature variation of IEC under typical test conditions. The weather in the testing period is hot and dry with the dry-bulb temperature of around 36.5℃ and wet-bulb temperature of around 19℃. In the test, the primary air flow rate is 400 m^3/h, the secondary/primary air flow rate ratio is 1 and spray water flow rate is 200L/h.

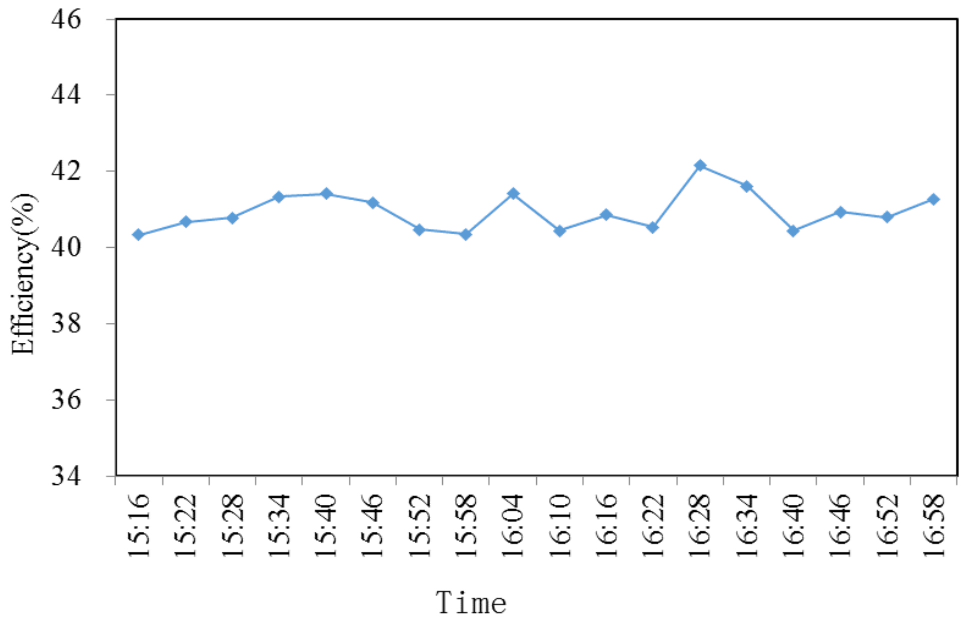


Fig. 16 Dynamic IEC efficiency of testing period

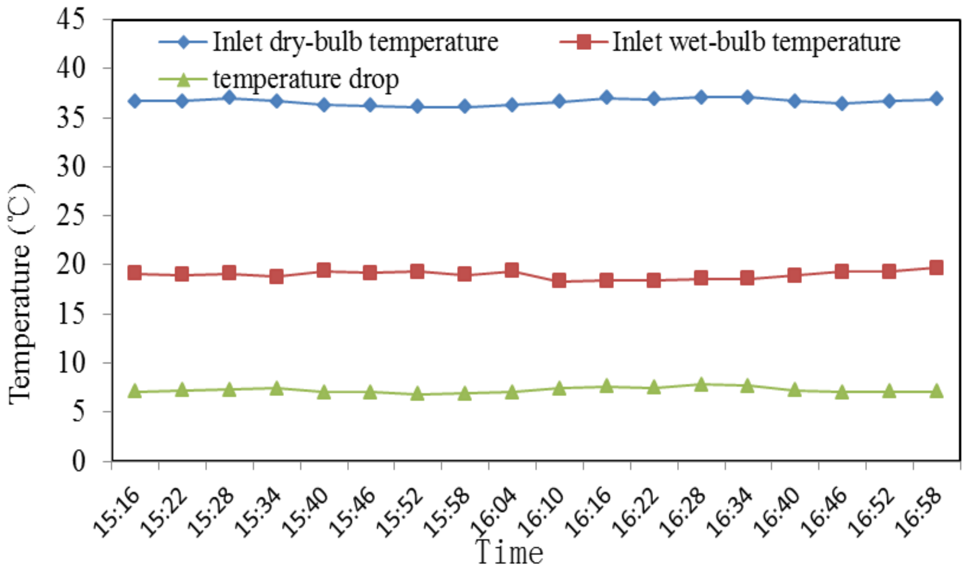


Fig. 17 Temperature under the dry weather changes over time

It can be seen from Fig.16 and Fig.17 that the porous ceramic IEC operates stably in 1.5 hours' testing period. The wet-bulb efficiency fluctuated in a small range from 40.3% to 42.2%. The average efficiency is calculated to be 41.0% and average temperature drop is 7.2℃. The efficiency is higher in the field test than that of lab test because of the drier weather condition enhances the water evaporation in the wet channels.

3.5 Performance comparison between porous ceramics IEC and other IEC

The performance of the novel porous ceramics IEC was compared with other IEC in term of wet-bulb efficiency, energy consumption and COP as shown in Table 5. The aluminum tube IEC is the traditional used IEC. The aluminum tube IEC covered by textile adopts enhanced mass transfer measure to improve the surface hydrophilicity. The tube length of the porous ceramics IEC is much smaller than the other two IECs in the literature and its number of heat transfer unit (NTU) is only around 1.1, so the wet-bulb efficiency is only 40%. However, according to the relationship between the NTU and wet-bulb efficiency derived from simulation results, the wet-bulb efficiency of the porous ceramics IEC can be improved to over 80% if the tube length increases to 1500mm. It can be seen from Table 5 that the COP of the porous ceramics IEC is much higher than the other two kinds of IEC mainly because of intermittent water spray.

Table 5 Performance comparison between porous ceramics IEC and other IEC

IEC type	Aluminum tube [20]	Aluminum tube covered by textile [13]	Porous ceramics
Tube length (mm)	1500	1530	600
Water spray mode	Continuously	Continuously	Intermittent
Wet-bulb efficiency	65%	74%	40%
Energy consumption (kWh/h)	4.45	2.82	1.11
COP	7.9	12.5	20.5 ~ 34.9

4. Conclusion

A novel porous ceramics tube type indirect evaporative cooler (IEC) is proposed in this paper to improve the surface hydrophilicity in the wet channels. A prototype was fabricated and tested under various operating conditions. The highlight results are given as follows:

1. The influence of secondary/primary air ratio (ranging from 0.5 to 1.1) is experimentally studied. It is found the wet-bulb efficiency improves with the increase of secondary/primary air ratio only if the air velocity is in a certain range. The optimal secondary/primary air flow rate ratio is 0.9 rather than 1.1 when the primary air velocity increases to 9.6 m/s.

2. The influence of spraying water flow rate (ranging from 250 to 0 L/h) is experimentally studied. It is found that the wet-bulb efficiency improves as the spray water rate decreases. The highest efficiency is achieved when the spray water flow rate is 0. It can be attributed to the superior water retention of the porous ceramic where the thin evaporation water film can be formed after being wetted.
3. The intermittent water spray is proposed for high-efficient operation of the porous ceramics IEC. The pump is optimized to intermittently operate for 5 minutes with the water flow rate of 150 L/h at 100 minutes interval. The energy consumption of pump is only 5% compared with that of the traditional IEC.
4. The sample porous ceramic IEC worked stable under typical hot and dry climate in Xi'an with the wet-bulb efficiency fluctuated in a small range from 40.3% to 42.2%.
5. The comparisons among the porous ceramics IEC, aluminum tube IEC and aluminum tube covered by textile IEC are made in term of wet-bulb efficiency, energy consumption and COP. The COP of porous ceramics IEC are found to be much higher than the other IECs.

The novel porous ceramics IEC studied in this paper provide a solution for solving the poor wettability problem in IEC. Besides, it improves the COP of IEC by intermittent water spray.

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