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R. Herrero Martín. Characterization of a semi-indirect evaporative cooler. Applied Thermal Engineering, 2009, 29 (10), pp.2113. 10.1016/j.applthermaleng.2008.09.008 . hal-00575234

HAL Id: hal-00575234

<https://hal.science/hal-00575234>

Submitted on 10 Mar 2011

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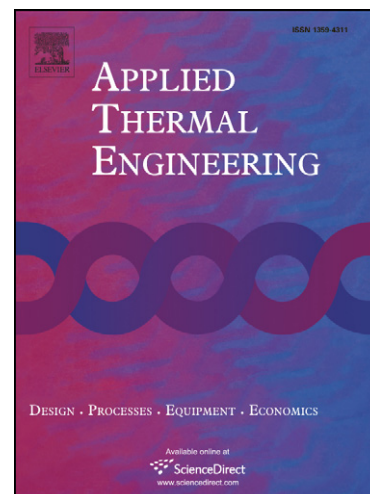
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PII: S1359-4311(08)00378-5
DOI: [10.1016/j.applthermaleng.2008.09.008](https://doi.org/10.1016/j.applthermaleng.2008.09.008)
Reference: ATE 2621

To appear in: *Applied Thermal Engineering*

Received Date: 26 March 2007
Revised Date: 8 September 2008
Accepted Date: 12 September 2008



Please cite this article as: R.H. Martín, Characterization of a semi-indirect evaporative cooler, *Applied Thermal Engineering* (2008), doi: [10.1016/j.applthermaleng.2008.09.008](https://doi.org/10.1016/j.applthermaleng.2008.09.008)

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CHARACTERIZATION OF A SEMI-INDIRECT EVAPORATIVE COOLER**R. Herrero Martín.**

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ABSTRACT

This paper presents the experimental study of a semi-indirect evaporative cooler (SIEC), which acts as an energy recovery device in air conditioning systems. Experimental measurements were achieved for the characterization of the thermal performance of the device, employing the design of experiments (DOE) methodology and an analysis of variance (ANOVA).

KEYWORDS: energy recovery, porous evaporative cooling, DOE, ANOVA.

INTRODUCTION

The energy cost, the environmental impact, the necessity of fulfilling established protocols, etc. force to reduce energy demand. This can be achieved using more energy efficient equipment. Evaporative cooling provides a low-cost, energy efficient and environmentally benign method of cooling. [1]

Most conventional direct evaporative cooling methods involve collection and recirculation of water to keep the wetting media or misting region saturated. There exists an environment of almost stagnant water in direct contact with the outside air, which aids, if not properly maintained at significant costs, the spread of many liquid phase-born bacterial diseases, most notably Legionnaire's disease. [2].

Due to this fact, indirect evaporative cooling application has been commonly used, in spite of the fact that indirect systems have lower efficiency in comparison with direct systems [3].

Semi-indirect evaporative systems with porous media are a successful attempt to improve the efficiency of indirect systems. Several prototypes for building cooling using porous ceramic materials as wetting media, as this paper proposes, have been built such as those by Ibrahim et al. [4] or Riffat and Zhu [5] who also combined an indirect evaporative cooler using porous ceramic as the cooling source and a heat pipe as the heat transfer device.

This paper presents the experimental study of a semi-indirect evaporative cooler (SIEC), which acts as an energy recovery device in air conditioning systems. For experimental characterization purposes, a complete factorial design was developed and an analysis of variance was performed to account for the contributory percentage of the analyzed factors and interactions which allowed to better understand the behaviour of the system.

EXPERIMENTAL APPARATUS

The semi-indirect evaporative cooler (SIEC) has two independent air flow supplies, one used for cooling, together with a second, the return air flow, in direct contact with water to favour heat and mass transfer. Water is forced against the return air flow and it is constantly circulating.

The cooling effect of the impulsed air would thus be the addition of two processes: the heat exchange between the two air flows (supply and return) plus the heat exchange process, through evaporation, between the air supply and the external wall.

The semi-indirect evaporative cooler works with the following mechanisms:

- Heat and mass transfer in the return air flow.
- Spread of mass due to porosity and heat transport through the solid wall.
- Evaporation or condensation as well as heat and mass exchange in the air flow supply.

All of these features are presented together, thus combining heat and mass transfer, increasing the cooling effect of the air to be conditioned and achieving optimisation of the thermal process. [6] Depending on the permeability of the wall of the solid porous cooler which separates the two air flows, there is greater or lower liquid diffusion

(water) towards the air flow supply from the external pores, in all cases. The partial pressure of the water vapour in the supply air is the controlling factor in this mass transport process. In this respect we have called it semi-indirect. In Tables 1, 2 the geometric dimensions and the staggered configuration of the ceramic exchanger are presented.

EXPERIMENTAL STUDY

As mentioned, the system is located in a recovery configuration to condition a room. The equipments used to carry out the experiments are the following: (Fig. 1)

Fig. 1

- Supply system: it consists on a fan with a potentiometer to keep the air flows under control.
- Air Handling Unit (A.H.U.): this equipment allows us to simulate the conditions of the air supplied (temperature and humidity).
- Air distribution System: all the measuring instruments are inserted there.
- Water distribution System: a water pump convey water from the tank to the pressure spray system with downward directed nozzles.
- A semi-indirect evaporative cooler.
- The conditioned room: the dimensions are 2x2x2.5 m, which contains a heat pump inside to guarantee when needed that the space is properly conditioned.
- Monitoring and Data-Acquisition system: a computer controls and stores all the results from the measuring instruments.

From the A.H.U. the air goes inside the SIEC. This main airstream is called the primary airflow and when this airstream is conditioned in the SIEC enters the room. Thus, the air expelled from the room goes through the SIEC in a cross-flow (recovery configuration), going up the SIEC until it leaves in the upper part (secondary airflow).

The measurement sensors used are:

- T: temperature measurement sensor. Type: Technoterm 60, Accuracy: 0.1°C.
- HR: relative humidity measurement sensor. Type: Honeywell HIH-3610, Accuracy: $\pm 2\%$ RH (0 – 100 % RH)
- DP: differential pressure transducer. Type: DWYER 603-2. Accuracy: (70 °F) $\pm 2\%$ scale range.

The characterization of the recovery system was carried out by following the experimental design method (DOE). A complete factorial design was applied to analyse latent and sensible heat recovered in order to obtain the total heat recovered by the evaporative cooling system.

The three factors analyzed were:

-Air Flow (V)

The three airflow levels are: 140 m³/h (V1), 260 m³/h (V2) and 380 m³/h (V3).

-Humidity level (HL)

The humidity levels corresponds to: Relative Humidity less than 30% (HL1), Relative Humidity between 30 and 60% (HL2), Relative Humidity more than 60% (HL3).

-Temperature (T)

The temperature levels are: 40°C (T5), 36.5°C (T4), 33°C (T3), 29.5°C (T2) and 26°C (T1).

Once the controlled factors and the corresponding levels are selected, an orthogonal design matrix was generated. The tests were randomized to avoid the possibility of creating an “order effect” as influenced by the sequence of the tests. All tests were replicated five times. Interactions between factors as well as the effects of individual factors were investigated. All the observations were corroborated by performing an analysis of variance (ANOVA). [7] The uncertainty values for the characteristics analyzed are shown in Table 3, where U_{v_i} represent the uncertainty values for each volumetric flow described [8].

EXPERIMENTAL DESIGN RESULTS

Sensible Heat Recovered:

The most remarkable results are shown in Figure 2 and Table 4. In Figure 2 the most contributory interaction $V \times T$, in terms of analysis of variance, is plotted against the mean sensible heat recovered. The results of the ANOVA carried out are shown in Table 4. Column 1 shows the factors analyzed, which are: volumetric flow rate, relative humidity level, temperature and the interactions between the aforementioned factors ($V \times HL$, $V \times T$ and $HL \times T$). Column 2 represents the degree of freedom (Dof) of the factors analyzed. Column 3 shows the sum of squares (SS) of the factors and column 4 gives the associated variance values (V) and in column 5 the contributory percentage is given (%).

The most significant conclusions which can be drawn from these results are presented below:

Airflow Analysis:

This factor has a medium contributory percentage close to 12% (Table 4). The energy recovered is proportional to the air flow due to the rise in the convection coefficient in the external flow.

Temperature Analysis:

As in common heat exchangers, the heat transfer rate is related to the temperature difference. When the temperature difference between the outdoor and the return airstreams rises, the sensible heat recovered is higher. Its contribution in terms of variance analysis is close to 12% (Table 4).

$V \times T$

This is the highest contributory percentage with a value of 45% (Table 4). There is no interaction between the factors, as can be clearly seen in Figure 2 which corroborates the individual factor analysis made. When the temperature and the airstream rise the sensible heat recovered also does. The continuity and the linearity of the

results are shown. A trend to negative values is clearly observed, thereby increasing the heat recovered. Thus, the best values are obtained for V3 and T5.

HLxT

It has a medium contributory percentage, close to 13% (Table 4). The maximum sensible heat recovered is linked to the lowest relative humidity value and the highest temperature level. Nevertheless, the near values of the different humidity levels for all the temperatures found explain the low contribution of the humidity single-factor.

Error

It should be underlined the high contributory percentage of the error (9%), higher than the humidity factor (4.5%). The explanation to this fact might be found after analysing the triple interaction VxHLxT, included in this percentage.

Latent Heat Recovered:

The most remarkable results are shown in Figure 3 and Table 5. In Figure 3 single factors are plotted against the mean latent heat recovered. The results of the ANOVA carried out are shown in Table 5. Column 1 shows the factors analyzed, which are: volumetric flow rate, relative humidity level, temperature and the interactions between the aforementioned factors (VxHL, VxT and HLxT). Column 2 represents the degree of freedom (Dof) of the factors analyzed. Column 3 shows the sum of squares (SS) of the factors and column 4 gives the associated variance values (V) and in column 5 the contributory percentage is given (%).

The most significant conclusions which can be drawn from these results are presented below:

Humidity Analysis:

This factor has the highest contributory percentage 38% (see Table 5). When the humidity level is low, evaporation takes place from the surface of the pipe. This humidity increment can lead to the appearance of condensation in the primary airflow, decreasing the humidity content (dehumidification process, which is linked to negative values of latent heat). (See Figure 2)

VxT

The contributory percentage is close to 15% (see Table 5), which expresses the importance of considering the synergy between both factors. Furthermore, it should be emphasized the predominant effect of dehumidification, (represented by negative mean values) and the proximity of the values, which explains the no contribution of the single factors.

HLxT

The contributory percentage is close to 29% (see Table 5). The behaviour of HLxT corroborates the single factor analysis. Air with low relative humidity and high temperature has a large evaporative capacity, while for the same temperatures, high humidity levels result in high specific humidity values and thus there are good conditions for the

appearance of condensation on the pipes (negative values of latent heat). The same effect can also be explained for low temperature values but the effect in the humidity gradient is lower. This fact yields to a decrease of the latent heat exchanged.

Total Heat Recovered:

The most remarkable results are shown in Figure 4 and Table &. In Figure 4 single factors are plotted against the mean total heat recovered. The most contributory interaction in terms of analysis of variance is HLxT. The results of the ANOVA carried out are shown in Table 6. Column 1 shows the factors analyzed, which are: volumetric flow rate, relative humidity level, temperature and the interactions between the aforementioned factors ($V \times HL$, $V \times T$ and $HL \times T$). Column 2 represents the degree of freedom (Dof) of the factors analyzed. Column 3 shows the sum of squares (SS) of the factors and column 4 gives the associated variance values (V) and in column 5 the contributory percentage is given (%).

The most significant conclusions which can be drawn from these results are presented below:

Temperature

This is an important factor especially in terms of sensible heat recovered. The total mean values become linearly more negative at higher temperature levels, when sensible and latent heat effects are added.

Humidity Level

This is the most contributory factor (40%). This is the determining factor in terms of latent heat. The mass transfer phenomena has priority over sensible heat recovered, fact in which lies the superiority of the SIEC over conventional indirect evaporative cooling systems where only sensible heat recovered is involved.

HLxT

At the lowest humidity level (HL1) the mean total heat recovered by adding sensible (negative values) and latent heat (positive values) is almost null. Nevertheless, this trend changes for the other humidity levels, especially for the highest temperature levels (T3, T4 and T5) where sensible heat and latent heat are both negative, due to the appearance of condensation, which corroborates the tendency previously observed in the single factors.

CONCLUSIONS

- The characterization of the SIEC system in terms of heat recovered was carried out by following the experimental design method. A complete factorial design was developed and an ANOVA was also performed to account the contributory percentage of the analyzed factors and interactions which allowed to better understand the behaviour of the system.
- For low relative humidity contents and high temperatures of the air supply, the main effect is evaporative from the surface of the ceramic pipes. For high temperatures and relative humidities of the air supply, dehumidification takes place and thus condensation appears in the exterior surface of the pipes and the latent

and sensible heat recovered are added (negative values). However, the mass transfer phenomena takes priority over sensible heat recovered.

- A possible use of this recovery system can be in climates with high temperatures and humidity, such as tropical environments where the system could reduce the humidity of the primary air supply, by using the cooling power of the secondary air.

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Figure 1- SIEC working mode and experimental set up.

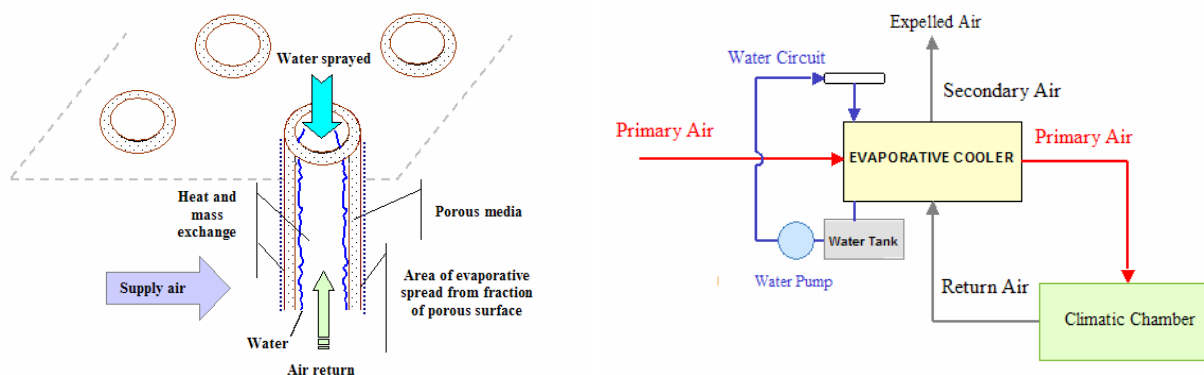


Figure 2.- Average Sensible Heat Recovered: $V \times T$ Contribution

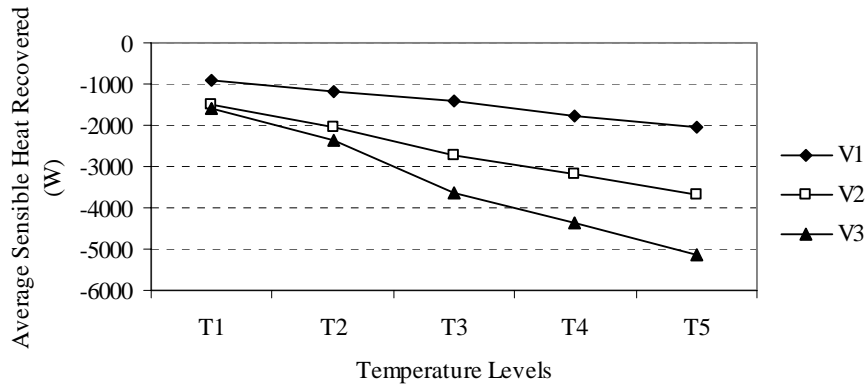


Figure 3.- Average Latent Heat Recovered: Factors Contribution

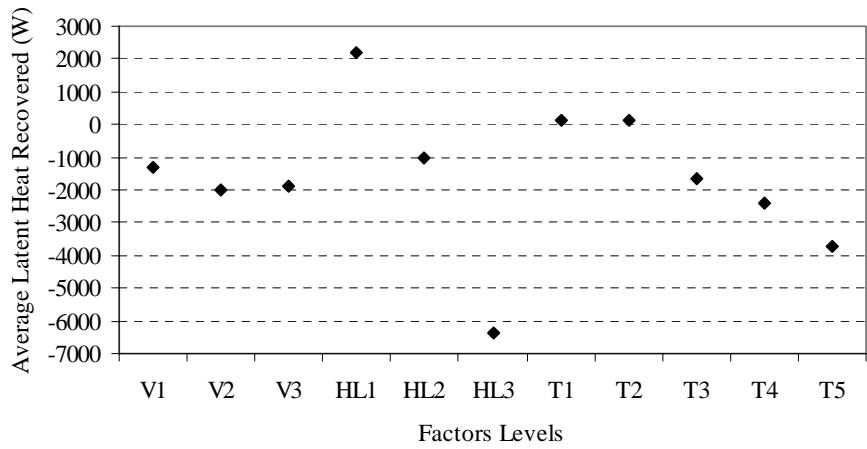


Figure 4.- Average Total Heat Recovered: Factors Contribution

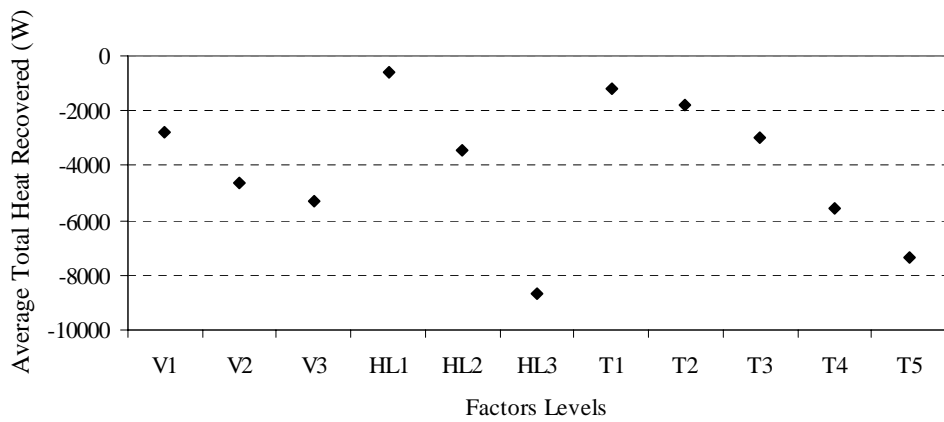


Table 1.-Geometric dimensions.

Internal diameter (di)	External diameter (de)	Thickness (δ)	Section T (S_T)	Section L (S_L)	Section D (S_D)	Pipe Length	Area (A_o)
$15 \cdot 10^{-3}$ m	$25 \cdot 10^{-3}$ m	$5 \cdot 10^{-3}$ m	$30 \cdot 10^{-3}$ m	$25 \cdot 10^{-3}$ m	$29,2 \cdot 10^{-3}$ m	0.6 m	2.3 m^2

Table 2.-Geometric configuration.

Arrangement	Number of columns	Number of rows	Number of pipes	Material
Staggered	7	7	49	Ceramic

Table 3.- Uncertainty values for the characteristics analyzed: sensible and latent heat [9]

(GUM procedures with $k=2$).

Humidity Level	Temperature ($^{\circ}\text{C}$)	Sensible Heat			Latent Heat		
		U_{V1} (%)	U_{V2} (%)	U_{V3} (%)	U_{V1} (%)	U_{V2} (%)	U_{V3} (%)
HL1	26.0	4.6	5.6	5.7	4.7	5.4	5.8
	29.5	4.5	6.1	5.6	4.7	6.1	5.6
	33.0	4.4	5.3	5.9	4.4	5.3	6.0
	36.5	4.4	5.0	5.5	4.5	5.1	5.4
	40.0	4.4	5.6	5.6	4.3	5.7	5.6
HL2	26.0	4.5	6.1	5.9	4.5	6.3	6.1
	29.5	4.4	6.0	6.3	4.6	6.1	6.4
	33.0	4.4	6.1	6.0	4.5	6.1	6.3
	36.5	4.3	5.9	5.9	4.5	6.1	6.2
	40.0	4.3	5.7	6.0	4.4	5.7	6.0
HL3	26.0	4.5	6.1	6.4	4.6	6.4	6.6
	29.5	4.4	6.2	6.3	4.5	6.3	6.4
	33.0	4.4	6.2	6.4	4.5	6.3	6.6
	36.5	4.3	5.3	6.4	4.5	5.6	6.4
	40.0	4.3	5.7	6.4	4.3	5.8	6.5

Table 4.- Sensible Heat Recovered: Analysis of Variance

Factors	Dof	SS	V	%
V	2	10455094	5227547	12.1
HL	2	3921981	1960991	4.5
T	4	10353009	2588252	12.0
VxHL	4	3549907	887477	4.1
VxT	8	39066823	4883353	45.0
HLxT	8	11607190	1450899	13.4
Error	16	7800599	487538	9.0
Total	44	86754603	1971696	100.0

Table 5.- Latent Heat Recovered: Analysis of Variance

Factors	Dof	SS	V	%
V	2	4066083	2033042	0,3
HL	2	559785313	279892657	38,0
T	4	110298594	27574649	7,5
VxHL	4	53314661	13328665	3,6
VxT	8	214917942	26864743	14,6
HLxT	8	422227501	52778438	28,7
Error	16	107661229	6728827	7,3
Total	44	1472271323	33460712	100,0

Table 6.- Total Heat Recovered: Analysis of Variance

Factors	Dof	SS	V	%
V	2	51414472	25707236	4.1
HL	2	502349284	251174642	40.0
T	4	250783927	62695982	20.0
VxHL	4	53135924	13283981	4.2
VxT	8	75952677	9494085	6.1
HLxT	8	209898618	26237327	16.7
Error	16	111277281	6954830	8.9
Total	44	1254812183	28518459	100