

## PARAMETRIC INVESTIGATION OF A COUNTER-FLOW HEAT AND MASS EXCHANGER BASED ON MAISOTSENKO CYCLE

by

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*The performance of a dew-point cooler is analyzed in terms of various parameters including dew point and wet bulb effectiveness. An experimental set-up of a counter-flow heat and mass exchanger based on Maisotsenko cycle evaporation technique is established. The set-up consists of 8 dry channels made of aluminum sheets and 7 wet channels made of kraft paper. Experimental analysis is performed under wide range of operating parameters including air absolute humidity: 12.7 g/kg to 18 g/kg, air temperature 20 to 55 °C, and inlet velocities 0.88 to 1.50 m/s. The results indicate that appreciably higher value of dew-point and the wet-bulb effectiveness can be achieved ranging up to a maximum of 93% and to 130%, respectively, at various inlet air conditions. Apart from the ambient air conditions, influence of amount of air diversion to wet side of channel is also studied. It is observed that this design feature of heat and mass exchanger can lead to a substantial increase of dew-point and wet-bulb effectiveness. By varying the inlet to wet side air ratio, a suitable limit of the quantity of inlet air diversion to working side is also suggested.*

Key words: *air conditioning, Maisotsenko cycle, dew point, counter-flow, sensible and latent heat*

### Introduction

Energy consumption has risen steeply over the past decade. Urbanization, fluctuations in energy prices, improvement in life style and reliance on fossil fuels has led scientists and engineers to find alternatives based on low cost, efficient, and greener technologies. According to one estimate, the total energy consumed by buildings across the world is between 30 to 40% [1] and about half of this energy is consumed to fulfill air-conditioning needs [2]. The demand for air-conditioning appliances is constantly increasing throughout the world. Around 95% of air-conditioning appliances utilize vapor-compression systems for cooling purposes [3, 4]. With high carbon footprint, these systems consume substantial amount of energy and are far less energy efficient.

Few promising alternate technologies especially based on desiccant air conditioning systems have been realized including Maisotsenko cycle (M-cycle) consuming lesser energy [5]. Maisotsenko cycle uses the idea of indirect evaporative cooling of air having a specially designed heat and mass exchanger (HMX) which cools the incoming air below the wet-bulb

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temperature without addition of undesired humidity [6]. The HMX design includes dry channels to pre-cool the working air before being diverted to wet side, thereby allowing higher effectiveness compared to conventional methods. M-cycle based HMX can be easily integrated in conventional desiccant systems which typically include desiccant wheel and heater. In moderate climatic conditions, the ambient air does not require dehumidification before it is delivered to the conditioned space, however without dehumidification; the evaporative cooling process is less effective [7]. While solar power can be utilized for heating or regeneration purpose thus making the whole system environment friendly. M-cycle based HMX in such conditions can be of benefit compared to conventional method as it can work well even at lesser effective dehumidification. Thus allowing wider application of desiccant technologies in areas where these systems are expected to be less useful [8].

Apart from M-cycle several other related methods and techniques have also been proposed. For instance, Ray [9] suggested a technique by coalescence of direct and indirect processes to decrease the temperature of surrounding ambient air below its wet-bulb temperature without the use of conventional mechanical refrigeration systems. Banks and Maclaine-Cross [10] theoretically examined the transfer of heat due to evaporation in a regenerative cooling process. The linear slope for saturated enthalpy-temperature relation of air was assumed and a modified model was proposed that can predict performance of cooler by analogy to heat exchangers of dry surface. The results suggested that the regenerative cooling process has the capability to reduce the wet bulb temperature. Hsu *et al.* [11] theoretically and experimentally analyzed three different types of indirect and direct evaporative cooling systems with various configurations of air flow *i. e.* cross-flow, regenerative and counter-flow arrangements. Nevertheless, M-cycle based air cooling systems have demonstrated their performance and the ability to work independently as well as under hybrid set-ups [8]. However, these systems need further improvements in terms of their design and their performances need to be analyzed under various climatic conditions to enhance their applicability [12]. Several recent studies have used different designs configurations based on the idea of dew-point cooling or specifically M-cycle air cooling in different test/climatic conditions [8, 13-15]. However, little can be found in the literature where different designs are tested in varying yet controlled ambient conditions.

In the current study, an experimental analysis of an indirect evaporative cooling system based on a counter flow configuration of M-cycle is presented. The main objective of this experiment is to determine the set of operating conditions those results in high dew point and wet bulb effectiveness through an improved system design in terms of HMX flow configuration. The evaporative system was installed at Renewable Energy Resource Development Center (RERDC) of University of Engineering and Technology (UET), Taxila, Pakistan.

### **Fabrication of counter flow heat and mass exchanger**

The counter flow arrangement of HMX comprises of different passages of aluminum made 0.175 mm thick sheets which are evenly wicked by water through the 0.3 mm thick kraft paper on the wet side. Therefore, the total thickness of the channel wall is kept less than 0.5 mm in order to reduce the temperature difference across the channel wall [16, 17]

The overall set-up of HMX consists of a total of 8 wet and 7 dry passages with each passage of 4 mm in height. The diversion holes are of equal diameter having diameter of 4mm each. Each sheet has total of 12 channels or guides with 6 of them are dry channels each having length of 36 inches and 2.5-inch width. Each dry channel has four holes and the diversion of amount of inlet air to wet side is through these passages, controlled by an axial fan at the exit of working channels. A complete specification of HMX and evaporative cooler is listed in tab. 1.

It was observed that the aluminum sheets coated with Kraft paper can absorb and retain up to 260 g/m<sup>2</sup> of water. The aluminum channels, with wicked kraft paper on wet side, are stacked to form an array with separators between them. The plastic separators not only ensure uniform channel height moreover they act as guides for the air flow direction on the two sides. The acrylic guides are placed along the longer side (length-wise) of channels to form a counter flow pattern within the HMX. The arrangement is shown for wet and dry sides in fig. 1. The diversion of dry side air on to wet side is through a series of equal sized holes distributed in a manner to allow smooth diversion.

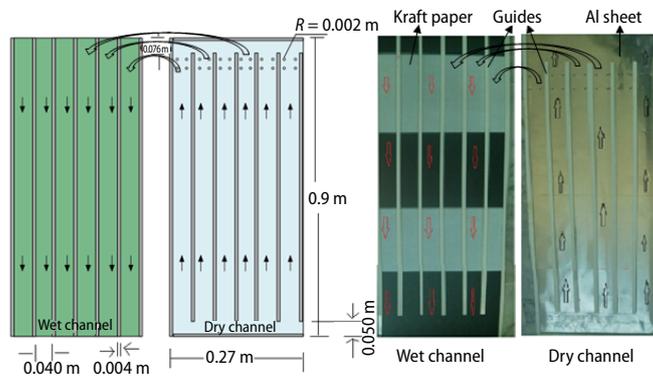
**Experimental set-up and measurements**

Extensive analysis of the HMX configuration is carried out over a wide range of inlet flow conditions. The upstream inlet flow condition chamber is purposely built to ensure smooth supply of air under the controlled conditions. The system enables control of upstream air dry bulb temperature as well as its absolute humidity, independently. The constant stream of air flow ranging from 60 °C to 20 °C (ambient temperature) with controllable absolute humidity varying from 10 g/kg to 20 g/kg is employed. This configuration allows study the effect of both inlet parameters independently, to an extent, in the intermediate ranges. At high (> 55 °C) temperatures keeping constant humidity levels is challenging, therefore the experiments are restricted to 53 °C.

The upstream controllable chamber, preconditioning unit, is equipped with temperature *i. e.* K-type thermocouples, humidity *i. e.* hygrometers and air speed *i. e.* hot wire anemometers measurement devices. All sensors are properly installed to measure the properties of uniform air in the duct. Specifications of all measuring devices are given in tab. 2.

**Table 1. Design values of the counter-flow system**

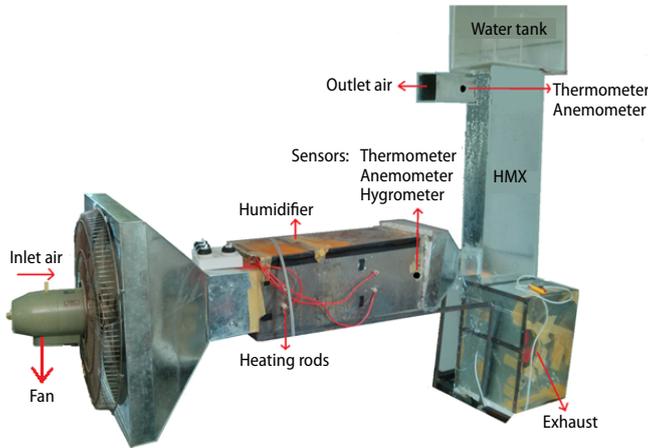
Parameters	Design value
Wall material	Aluminum coated with kraft paper
Wall thickness of composite wall [mm]	0.475
Length of dry channel [mm]	900
Length of wet channel [mm]	900
Width of channel [mm]	40
Channel gap [mm]	4
Working-to-intake air ratio	0.1-0.9
Kraft paper water absorption ability [gm <sup>-2</sup> ]	260
Fabric (kraft paper) conductivity [Wm <sup>-1</sup> K <sup>-1</sup> ]	0.049



**Figure 1. Schematic diagram (a) and real view (b) of a dry and wet channel for single pass**

**Table 2. Specifications of measuring instruments**

Parameters	Measuring devices	Accuracy	Measurement range
Temperature	K-type thermocouple	+ 0.2 °C	0-100 °C
Air velocity	Hot-wire anemometer	+ 5%	0.2-20.0 m/s
Humidity	Hygrometer	+ 1% RH	0-100% RH



**Figure 2. Experimental set-up with labeling of all units and instrumentation points**

control the inlet conditions with a total of 4 kW heating coils for heating of inlet air while a honeycomb cooling media is employed to change humidity of inlet air. Intake air flow is controlled through a variable speed controller. It is pertinent to mention that the experimental study of this HMX along with flow arrangement and the ranging of inlet flow parameters is quite rare, as indicated in the literature survey. Therefore, the results presented here under the controlled conditions offer good insight of the working of HMX.

### Performance parameters of the system

The performance of the dew point evaporative cooling system is gauged in terms wet-bulb,  $\varepsilon_{wb}$ , and dew-point,  $\varepsilon_{dp}$ , effectiveness by considering wet bulb and dew point temperature, respectively:

$$\varepsilon_{wb} = \frac{t_{a,in} - t_{a,out}}{t_{a,in} - t_{wb,in}} \quad (1)$$

$$\varepsilon_{dp} = \frac{t_{a,in} - t_{a,out}}{t_{a,in} - t_{dew,in}} \quad (2)$$

Here  $t_a$  is the dry bulb temperature of the air while subscript *in* and *out* demarcates the inlet and outlet. While  $t_{dew,in}$  and  $t_{wb,in}$  are the dew point and wet bulb temperatures of the inlet air, respectively.

### Results and discussion

In the current study, the effect of various inlet conditions including absolute humidity, temperature, air flow rate, and air partition ratio on product air outlet temperature and system effectiveness is presented.

#### *Effect of inlet absolute humidity*

Effect of variation of inlet absolute humidity,  $\omega$ , on the product air outlet temperature is presented in fig. 3. It can be observed that the lower absolute humidity level at the inlet can lead to greater drop in the temperature of product air at the outlet. If the condition of inlet air is

Moreover, the air speed, temperature and humidity levels are measured at both exits (wet as well as dry sides). The configuration of counter flow HMX along with upstream and downstream ducting and labeling of positions of measurement equipment is shown in fig. 2 (insulated view).

Apart of dew point heat and mass exchanger, the set-up also includes tangential fan for supply air axial fan for exhaust air control, water sprinkler, water tank, water pump, and float switch for controlling water flow. The pre-conditioning unit is installed to

hot and dry (*i. e.*, above 40 °C for  $\omega = 12.7$  g/kg), the outlet temperature is observed to be around 1 °C lower than the similar inlet conditions but at higher humidity,  $\omega = 18$  g/kg. This substantial drop of temperature of product air can be explained in terms of psychrometric energy. Psychrometric energy is the amount of energy which is spent by the product air to humidify the vapor-air mixture of working side so that it reaches its saturated state. As the absolute humidity of product air does not change, therefore psychrometric energy can be estimated

in terms of change in dry bulb temperature on a standard psychrometric chart. Thus, in order to reach the dew point, without change in absolute humidity as in the case of product air, the straight line progresses horizontally to its dew point temperature. The lower the absolute humidity of air, the greater the difference is between the initial and dew point temperatures.

For the working air, the lower humidity levels of hot air have greater potential to absorb moisture which subsequently leads to reduction in the product air temperature through sensible cooling. Moreover, the difference of outlet temperatures for moderate to low inlet temperatures grows larger when inlet humidity levels increase. For instance, inlet air temperature of around 28 °C yields 22.3 °C at the outlet for  $\omega = 18$  g/kg while significantly lower value of 20.7 °C is observed for  $\omega = 12.7$  g/kg. This clearly marks the fact that the higher availability of psychrometric energy leads to greater temperature drop. This effect is clearly noted in fig. 4 where dew point effectiveness is shown for the same flow conditions as in fig. 3. Although dew point effectiveness at  $\omega = 18$  g/kg is larger than the same inlet conditions with  $\omega = 12.7$  g/kg, however the apparent drop in product temperature is higher in the latter case. This can be explained by the non-linear variation of dew point at a given temperature with variation of absolute humidity. At higher values of absolute humidity, the dew point temperature is reached earlier, in terms of dry bulb temperature. Therefore, the higher dew point effectiveness (maximum 93%) is achieved at  $\omega = 18$  g/kg compared to a maximum of 81% dew point effectiveness at  $\omega = 12.7$  g/kg. Subsequently, the dew point effectiveness decreases with decrease in inlet air temperature at a given absolute humidity reaching the lowest value of 53% at 25.5 °C and  $\omega = 12.7$  g/kg.

#### Effect of inlet air flow rate

In another set of experiments, the influence of inlet air velocity is studied at varying inlet temperatures while keeping the absolute humidity constant ( $\omega = 14.4$  g/kg). Apparently, in fig. 5, the influence of low inlet velocity is evident on the outlet product air temperature with larger temperature drop (above 40 °C). This has been noted earlier under cross-flow configuration [18].

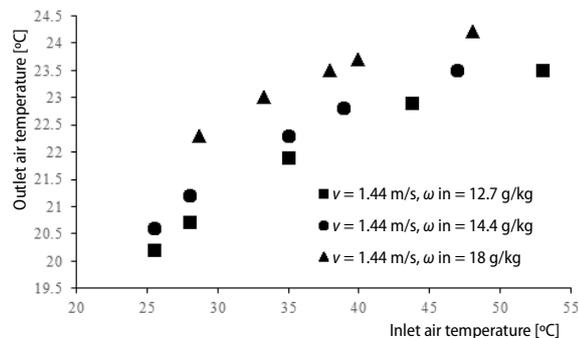


Figure 3. Outlet and inlet dry bulb temperatures at constant inlet velocity with varying absolute humidity  $\omega$

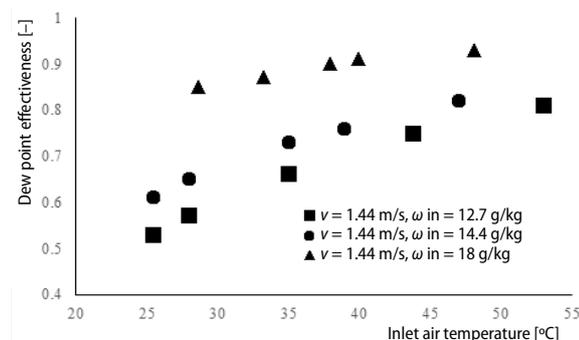
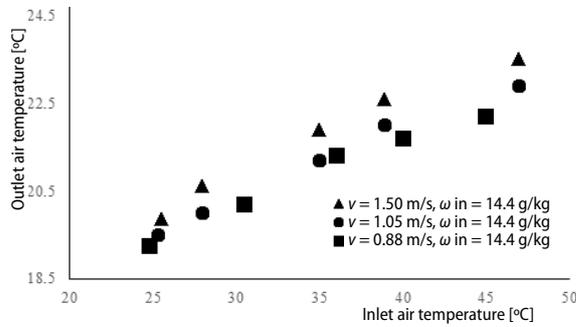
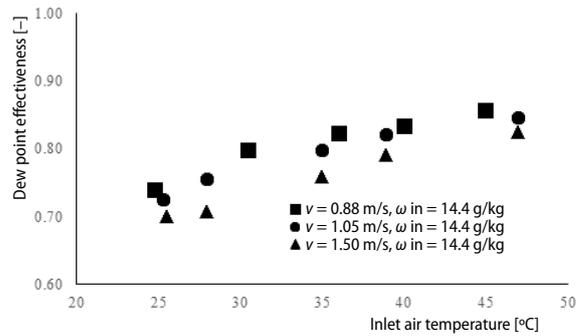


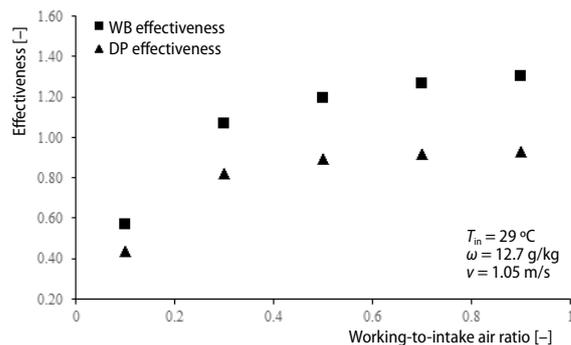
Figure 4. Variation of dew point effectiveness at various inlet air temperatures and absolute humidity levels with fixed inlet air velocity



**Figure 5.** Variation of outlet product air temperature with change in inlet air temperature at varying air speeds; the absolute humidity of inlet air is fixed



**Figure 6.** Variation of dew point effectiveness at various inlet air temperatures and inlet air velocity with fixed absolute humidity levels



**Figure 7.** Variation of dew point and wet bulb effectiveness at various working to intake air ratios

side, the increase in dew point as well as wet bulb effectiveness is minimal. This suggests that for sustainable working of this configuration, the guideline working to inlet air ratio is 40%. This ensures sufficient amount of product/dry side air as well as reasonable dew point effectiveness.

The dew point effectiveness deviation is around 15% with variation in the inlet air dry bulb temperature. The trends at different inlet air velocities are almost similar with the highest dew point effectiveness (~86%) noted at lowest inlet velocity (0.88 m/s). Based on the results shown in figs. 4 and 6 for dew point effectiveness, it can be concluded that for a given geometrical conditions and inlet air temperatures, the change in absolute humidity has significant influence on the performance of the HMX compared to change in the inlet air velocity.

#### *Effect of inlet air flow partition to working channel*

The influence of amount of diversion of inlet air flow rate towards working channel is also an important parameter apart from aforementioned flow parameters. This is one of the design features of the HMX which can be used to manipulate its performance under varying inlet air conditions. The ratio of working to inlet air flow rate can be maneuvered by introducing a fan at the exit of the working channel. The selector switch at the exit fan regulated the amount of working side flow rate. In essence, it influences the net amount of heat and mass been exchanged within the HMX. Selecting an appropriate ratio of inlet to working air flow is important, as it leads to substantial decrease in amount of supply air.

Diverting all the air to working side can lead to significant increase of dew point as well as wet bulb effectiveness as shown in fig. 7. However, it can be noticed that if the ratio exceeds 0.4, *i. e.* 40% of inlet air diverted to working

## Conclusions

This work focuses on the detailed performance analysis of a simple counter flow Maisotsenko cycle based air cooler. The heat and mass exchanger, designed on the counter flow arrangement, is placed in duct with upstream chamber which allows control of flow properties such as inlet air velocity, its dry bulb temperature and absolute humidity. Here all these parameters are studied independently in terms of dew point effectiveness of the HMX. It can be concluded that higher values of dew point effectiveness ( $> 80\%$ ) are generally achieved at higher inlet absolute humidity, low air speeds and high inlet temperatures. However, higher dew point effectiveness does not reflect in to lower outlet temperatures. Instead, a greater drop of outlet temperature is directly linked with lower absolute inlet humidity.

Apart from the inlet air condition, a simple design feature of HMX can be used to control the effectiveness of the cooler. By controlling the working to inlet air ratio, the dew point effectiveness can be significantly improved, however at the cost of product/dry side air loss. It is noted that a suitable range of working to intake air ratio can be devised to achieve reasonable dry side air supply as well as significantly higher dew point effectiveness. In the current experimental set up any increase of inlet to working air ratio more than 40% produced minimal improvements in the dew point/wet bulb effectiveness.

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