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Thermal performance of desiccant-integrated and conventional Maisotsenko cooling systems in a high humidity tropical climate

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Abstract

Tropical regions are characterized by a distinctive climate, marked by consistently high temperatures and significant humidity throughout the year. These conditions necessitate the use of cooling systems to ensure thermal comfort. Previous studies have shown that the Maisotsenko cooling system experiences a decline in efficiency when operating in high-humidity environments. Conversely, desiccant systems are effective in reducing air humidity. This study aims to design and experimentally evaluate the performance of a Maisotsenko cooling system under high-humidity tropical conditions, as well as the effect of integrating a desiccant system on its cooling efficiency. The experiments were conducted using a laboratory-scale fabricated test rig, consisting of a Maisotsenko cooling unit with a channel length of 180 mm and a desiccant unit with a channel length of 140 mm. Tests were performed using a standalone Maisotsenko system and a combined Maisotsenko-desiccant system. Air velocity was varied at 3 m/s, 4 m/s, and 5 m/s, with an air ratio of 0.5. The results showed that for the Maisotsenko system without a desiccant, the best cooling performance under high humidity conditions occurred at an air velocity of 3 m/s, achieving a temperature reduction of 1.7°C, a heat transfer rate of 1.4 W, a dew point temperature effectiveness of 27.5%, and a wet-bulb temperature effectiveness of 37.3%. In contrast, the combined system with a desiccant at 3 m/s provided enhanced temperature reduction, dew point effectiveness, and wet-bulb effectiveness of 2°C, 32.4%, and 43.8%, respectively. The highest heat transfer rate, however, was recorded at 5 m/s with a value of 1.9 W. The integration of a desiccant system significantly improved the cooling performance of the Maisotsenko system in terms of temperature reduction, heat transfer rate, and cooling efficiency. At air velocities of 3 m/s, 4 m/s, and 5 m/s, the cooling performance increased by 17.6%, 78.9%, and 366.7%, respectively.

Keywords:
Maisotsenko cooling system, desiccant system, efficiency, tropical climate, humidity.

1 Introduction

Tropical regions are characterized by persistently high air temperatures and relative humidity throughout the year. Air humidity in these regions typically ranges from 60% to 90% with minimal seasonal variation, driven by intense solar radiation, frequent precipitation, and high evaporation rates from both ocean surfaces and dense tropical vegetation [1][2][3][4]. Strong atmospheric convection near the equator sustains high relative humidity levels throughout the troposphere [5].

High humidity has a profound impact on thermal comfort, energy demand, and the effectiveness of cooling systems, particularly those based on evaporative principles [6]. When relative humidity approaches saturation, the driving force for evaporation diminishes, reducing the effectiveness of direct evaporative cooling systems [7].

The Maisotsenko Cycle (M-Cycle) is a form of indirect evaporative cooling that utilizes a regenerative heat and mass exchanger to cool air closer to the dew point temperature without increasing its humidity [8][9]. The M-Cycle offers benefits such as low energy consumption, no use of refrigerants, and minimal environmental impact [10].

However, studies have shown that the performance of M-Cycle systems is significantly influenced by environmental conditions, especially humidity. In tropical climates, where relative humidity consistently exceeds 70% [11][12], the small temperature difference between dry-bulb and dew point limits the evaporative cooling potential [13]. High partial pressure of water vapor reduces the effectiveness of heat and mass exchange between the working and product air streams [14].

Previous studies have demonstrated the sensitivity of the M-Cycle to climatic parameters. For instance, Cheng [15] found that inlet air velocity and air ratio significantly affect system performance. Razavi *et al.* [16] emphasized that lowering the operating air ratio can enhance system efficiency. However, Fan *et al.* .[17] and Wang *et al.* [18] reported performance degradation under high humidity conditions, common in tropical settings. These limitations hinder the broader adoption of the Maisotsenko system in regions where it could otherwise offer substantial environmental and economic benefits.

Several researchers, including Cui *et al.* [19], have noted that M-Cycle systems perform optimally under moderate humidity but require enhancements to function well in high humidity conditions. Gao *et al.* [20] suggested integrating desiccant dehumidification systems to precondition incoming air, reducing its humidity level and thereby improving the efficiency of the M-Cycle.

Desiccant systems absorb moisture from the air using hygroscopic materials such as silica gel, lithium chloride, or calcium chloride. These systems have demonstrated effective humidity control capabilities and can operate using solar or waste heat sources [21][22][23]. The integration of desiccant and evaporative systems has been proposed as a sustainable alternative to conventional vapor-compression cooling in humid climates [24][25].

Despite promising theoretical models, experimental validation of integrated desiccant and M-Cycle systems remains limited, particularly under conditions simulating tropical climates. Most studies have focused on simulations or dry climate scenarios [26][27][28][29]. Therefore, this study aims to experimentally investigate the performance of a hybrid Maisotsenko-desiccant cooling system under controlled humid conditions.

The system will be tested at three different air velocities, namely 3 m/s, 4 m/s, and 5 m/s, under laboratory conditions designed to simulate a tropical environment. Key performance indicators such as temperature reduction, heat transfer rate, cooling efficiency, and dew point effectiveness will be analyzed. The goal is to assess the extent to which a desiccant system can enhance the M-Cycle's performance in high-humidity settings and to provide practical design insights for sustainable cooling applications in tropical regions.

2 Method

2.1 Cooling and desiccant system design

This subsection describes the working principles and components of the experimental Maisotsenko cooling system and the desiccant system used in the testing procedures. Fig. 1 illustrates the Maisotsenko cooling system along with its main components. The working mechanism of the Maisotsenko system, along with the function of each component, is explained as: (1) air inlet: the air inlet serves as the entry point through which ambient air enters the Maisotsenko cooling system. The air is then directed into the internal channels, where it undergoes the cooling process; (2) dry channel: the dry channel is the section of the Maisotsenko system where ambient air flows without undergoing evaporative cooling. In this region, no moisture is added, and the air's humidity remains unchanged. However, heat transfer by convection occurs through the separating wall from the adjacent wet channel. The air in the dry channel that has undergone sensible cooling then flows out as product air, but a portion of that air is directed into the wet channel, where it is referred to as working air; (3) wet channel: the wet channel functions as the pathway for ambient air that is utilized as working or cooling air. The presence of a moistened layer on the separating wall within this channel enables evaporative cooling to take place. As a result, the air in the wet channel absorbs heat from the dry channel through the wall, facilitating a temperature drop in the dry air, which is then referred to as product air; (4) channel wall: the channel wall acts as a thermal barrier that prevents unwanted heat exchange between the internal airflow and the external environment. This ensures the system maintains thermal integrity and performance efficiency; (5) separating wall and moist layer: the separating wall divides the dry and wet channels, allowing the wet-side air to undergo evaporative cooling while preventing moisture transfer to the dry air. This design ensures that the product's air remains at a lower temperature without increased humidity. The moist layer serves as the medium supplying water to the wet channel, enabling continuous evaporative cooling of the working air; (6) product air outlet: the product air outlet is the exit point for the dry air that has undergone heat exchange with the working air. As a result of this process, the product air exits the system at a lower temperature than the ambient air; (7) working air outlet: the working air outlet is where the working air, having gone through the evaporative cooling process in the wet channel, is discharged. This air typically has a lower temperature and higher humidity compared to the incoming ambient air.

Fig. 2 presents the desiccant system and its constituent parts. The operating principle of the desiccant system and the role of each component are described in detail as: (1) air inlet: the air inlet is a component of the desiccant system that functions as the entry point for ambient air. This incoming air is then directed through the desiccant unit for humidity reduction; (2) desiccant layer: the desiccant layer refers to the coating of hygroscopic material adhered to the inner surface of the duct. Its primary function is to absorb moisture from the incoming air, thereby reducing its humidity level before it progresses further through the system; (3) channel wall: the channel wall in the desiccant system serves as a thermal and environmental barrier, isolating the internal air-drying process from any external air interference, thus maintaining system performance and integrity; (4) desiccant duct: the desiccant duct is the main passage within the system where the air dehumidification process takes place. Inside this channel, the air interacts with the desiccant material to remove moisture content effectively; (5) air outlet: the air outlet is the exit point for the processed air that has undergone dehumidification. By the time it reaches this section, the air has a significantly lower humidity level compared to when it entered the system.

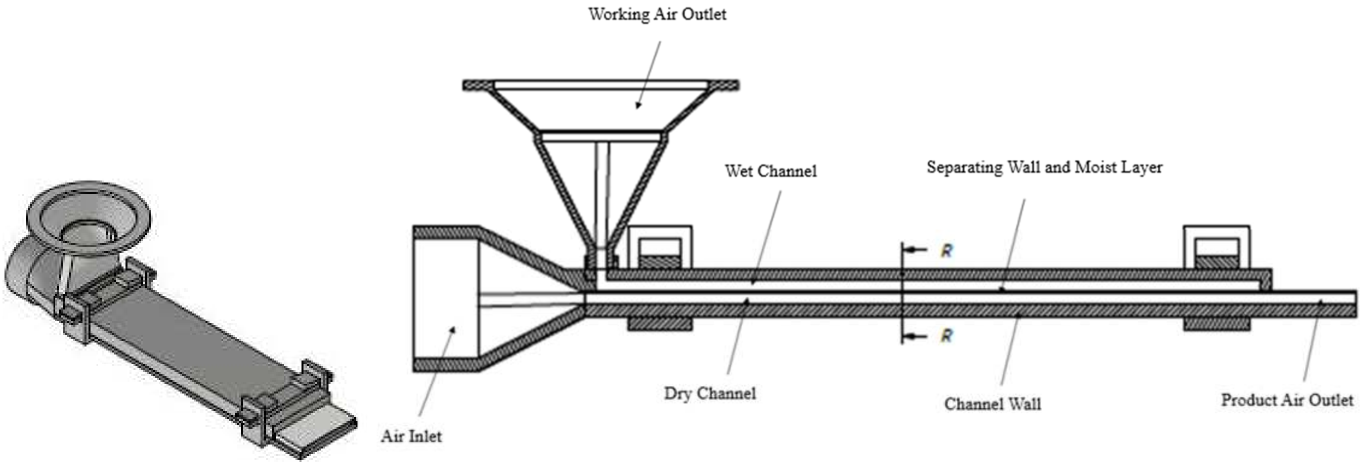

Fig. 1. Maisotsenko cooling system.

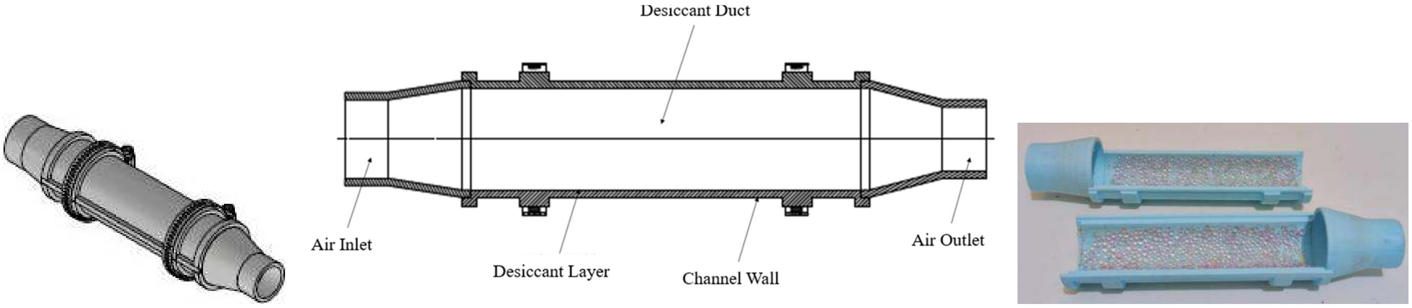

Fig. 2. Desiccant system.

2.2 Equipment design

The experimental apparatus consisted of a laboratory-scale Maisotsenko cooling system and a desiccant system, both fabricated using a 3D printer (refer to Fig. 3 and Fig. 4).

The laboratory-scale Maisotsenko cooling system was designed without a water regeneration system; therefore, the apparatus was configured so that both air channels could be separated to allow manual re-wetting of the water film in the wet channel.

The specifications of the designed Maisotsenko cooling system are: channel length: 180 mm, channel width: 35 mm, channel height: 2.5 mm, wall thickness: 3.5 mm, separator wall thickness: 0.5 mm, inlet diameter: 27 mm, exhaust diameter: 50 mm, fan outlet diameter: 23 mm, main material: Polylactide filament, separator wall material: aluminum, water film material: creped cellulose paper.

Similarly, the desiccant system was designed without a desiccant material regeneration mechanism, and was instead configured for manual refilling of the desiccant material. The desiccant material used was 20 grams of silica gel, which functions to absorb moisture content from the air, thereby reducing its humidity level.

The specifications of the designed desiccant system are: channel diameter: 35 mm, channel length: 140 mm, wall thickness: 2.5 mm, inlet diameter: 27 mm, outlet diameter: 22 mm, main material: Polylactide filament, desiccant material: silica gel.

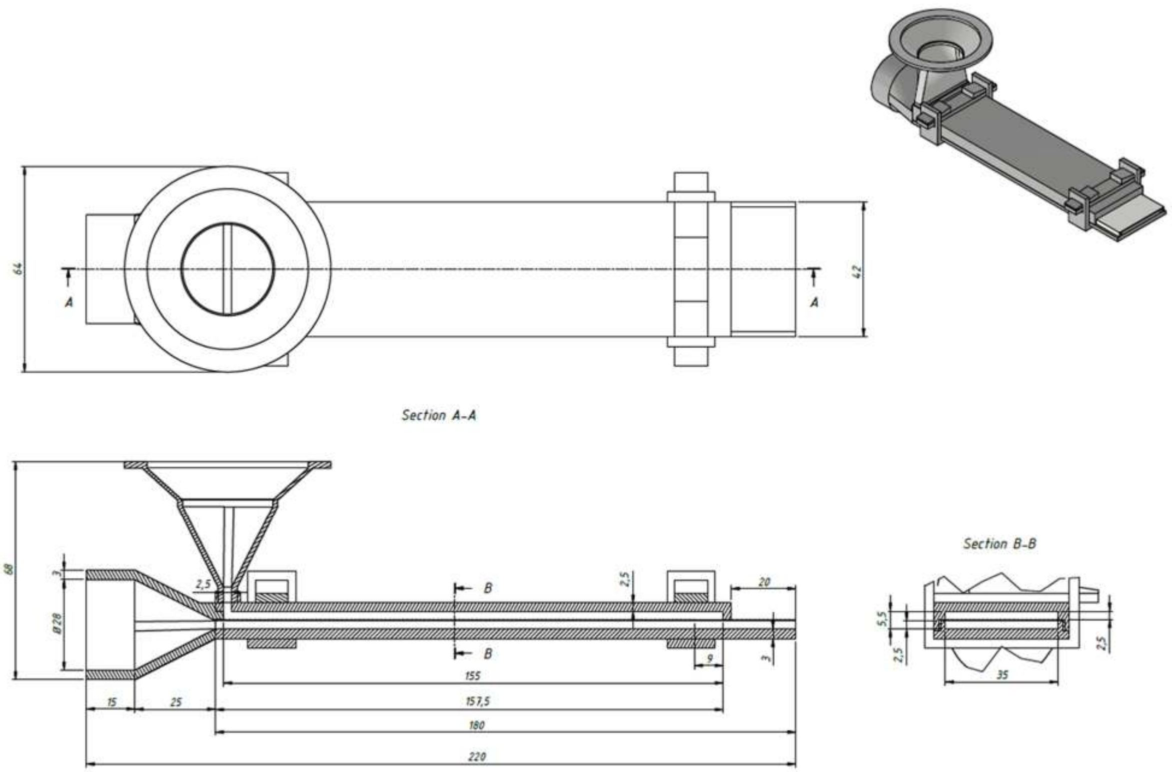

Fig. 3. Maisotsenko cooling system design.

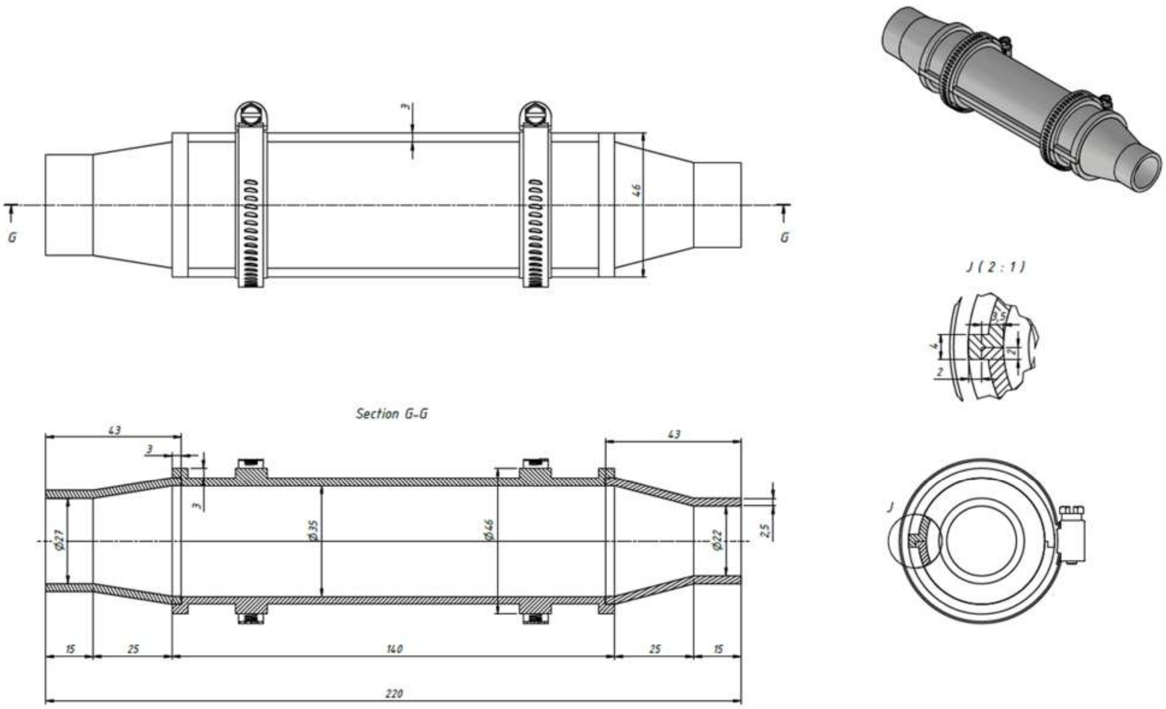

Fig. 4. Desiccant system design.

2.3 Testing setup

The testing and data collection procedures were carried out on two variations of the experimental setup: the standalone Maisotsenko cooling system (Fig. 5) and the Maisotsenko cooling system with an additional desiccant system (Fig. 6). For both configurations, the input variable was set at measurement point 1, where the airflow ratio between the dry and wet channels was maintained at 0.5, with a channel width of 2.5 mm. The experiments were conducted under ambient room temperature and humidity conditions, using three variations of air velocity: 3 m/s, 4 m/s, and 5 m/s. The ambient air temperature and humidity for testing parameters were recorded at 32.3°C and 70% respectively.

In the testing of the standalone Maisotsenko cooling system, temperature and humidity measurements were taken at three points: the inlet air, the outlet product air, and the outlet working air.

Meanwhile, for the Maisotsenko cooling system with an additional desiccant unit, as shown in Fig. 6, temperature and humidity were measured in the inlet air, outlet desiccant air, outlet product air, and outlet working air.

Exhaust Fan

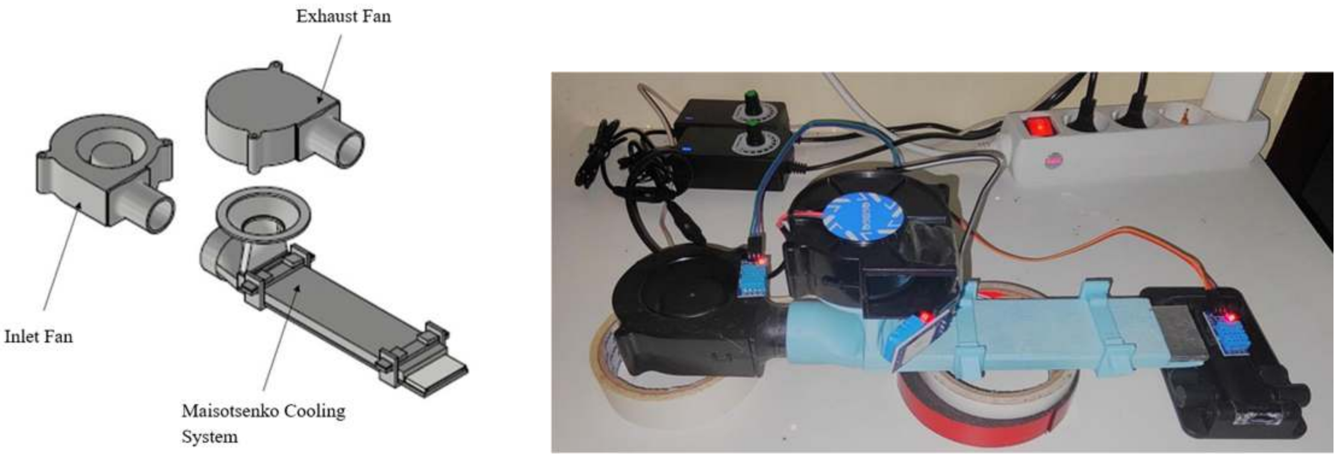

Fig. 5. Standalone Maisotsenko experiment setup.

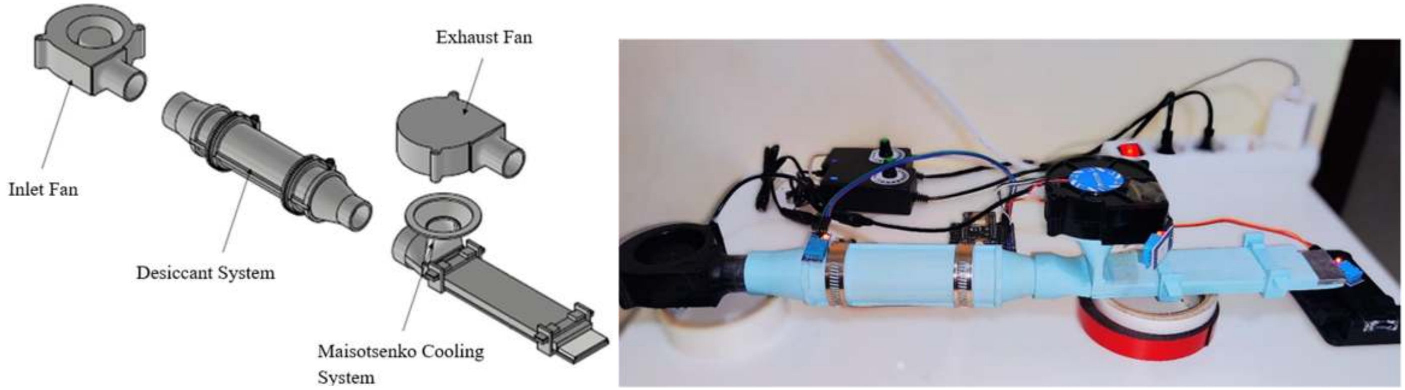

Fig. 6. Experimental setup of the Maisotsenko system coupled with a desiccant system.

The data were recorded using a data acquisition system integrated with a microcontroller unit, which provides real-time data collection at multiple measurement points. DHT11 sensors were used to measure air temperature and humidity. The fan speed was controlled by potentiometers attached to the inlet and exhaust fans, while the air velocity was measured and calibrated using an anemometer.

The data obtained from these tests will be used to analyze the performance of the Maisotsenko cooling system under humid air conditions and to assess the impact of a desiccant system on its cooling performance.

2.4 Maisotsenko cooling system performance

The performance of the Maisotsenko cooling system was evaluated using dew point thermal efficiency, wet-bulb thermal efficiency, and cooling capacity as defined in Eq. (1)-Eq. (3).

2.4.1 Dew point thermal efficiency

Dew point thermal efficiency (η_{dp}) represents the effectiveness of the cooling system in approaching the inlet air dew point temperature and is expressed as the ratio between the temperature difference of the inlet and outlet air and the temperature difference between the inlet air temperature and its dew point temperature (Eq. (1)), where η_{dp} is the dew point efficiency (%), T_{in} is the inlet air temperature (K), T_{out} is the outlet air temperature (K), T_{dp} is the dew point temperature (k).

$$\eta_{dp} = \frac{T_{in}-T_{out}}{T_{in}-T_{dp}} \tag{1}$$

2.4.2 Wet-bulb thermal efficiency

Wet-bulb thermal efficiency (η_{wb}) is a measure of how effectively a cooling or heat transfer process reduces the fluid temperature toward the wet-bulb temperature. It is defined as the ratio of the actual temperature drop of the fluid to the maximum possible (theoretical) temperature drop, which is the difference between the inlet temperature and the wet-bulb temperature (Eq. (2)), where η_{wb} is the wet-bulb thermal efficiency (%), T_{in} is the inlet air temperature (K), T_{out} is the outlet air temperature (K), T_{wb} is the wet bulb temperature (k).

$$\eta_{wb} = \frac{T_{in}-T_{out}}{T_{in}-T_{wb}} \tag{2}$$

2.4.3 Cooling capacity

Cooling capacity is the rate at which a cooling system removes heat from a fluid, determined by the mass flow rate, the fluid's specific heat capacity, and the temperature difference between the inlet and outlet. Mathematically, the cooling capacity is expressed as Eq. (3), where $\dot{Q}$ is the cooling capacity (kW), $\dot{m}$ is the fluid mass flow rate (kg), c_p is the specific heat capacity (kJ/kg·K), T_{in} is the inlet air temperature (K), T_{out} is the outlet air temperature (K).

$$\dot{Q} = \dot{m}c_p(T_{in} - T_{out}) \tag{3}$$

3 Results and discussion

3.1 Comparative performance of the Maisotsenko cooling system

This subsection compares the performance of the standalone Maisotsenko cooling system with that of the system incorporating a desiccant, in order to evaluate the impact of desiccant integration on cooling performance. The results are presented graphically to facilitate visualization and analysis.

Fig. 7 illustrates the comparison of temperature reduction, defined as the temperature difference between the air inlet and the product air, for the Maisotsenko cooling system operating with and without desiccant integration. As shown in the figure, the incorporation of the desiccant system enhances the temperature reduction achieved during the cooling process. Furthermore, an increase in air inlet velocity leads to a decrease in the magnitude of the temperature reduction.

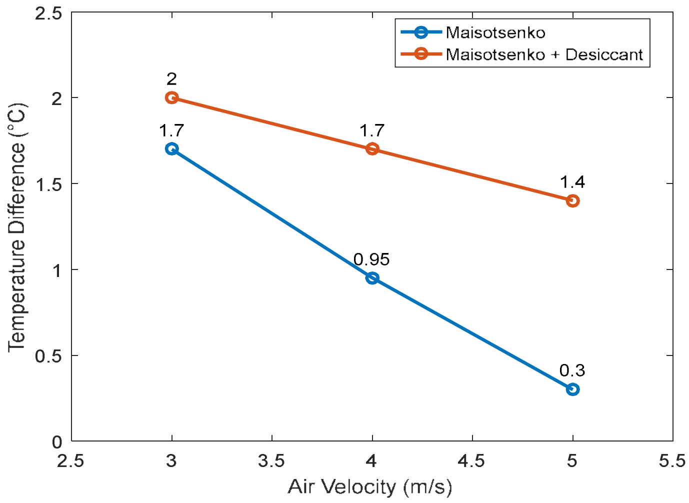

Fig. 7. Comparison of temperature reduction.

Fig. 8 presents a comparison of heat transfer rates for the Maisotsenko system operating with and without desiccant integration at various air inlet velocities. The results indicate that incorporating the desiccant system enhances the heat transfer rate during the cooling process. Furthermore, the Maisotsenko system with desiccant integration operating at an air inlet velocity of 5 m/s exhibits a higher heat transfer rate than those at 4 m/s and 3 m/s. In contrast, for a system without desiccant, the heat transfer rate increases as the air velocity decreases, whereas for the system with desiccant integration, the heat transfer rate decreases with decreasing air velocity.

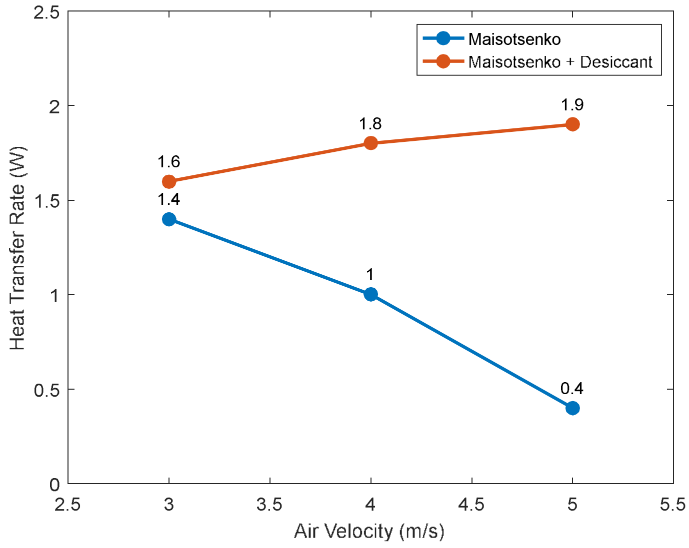

Fig. 8. Heat transfer rate comparison.

Fig. 9 and Fig. 10 present a comparison of dew point temperature efficiency and wet-bulb temperature efficiency between the standalone Maisotsenko system and the desiccant-assisted system. The results indicate that integrating a desiccant system into the Maisotsenko cycle improves both dew point temperature efficiency and wet-bulb temperature efficiency. In addition, both efficiencies increase as the air inlet velocity decreases.

Fig. 11 illustrates the improvement in the performance of the Maisotsenko cooling system with the integration of a desiccant system, in terms of temperature reduction, heat transfer rate, and efficiency. As shown in the figure, at an air velocity of 5 m/s, the cooling performance increased by 366.7%. At 4 m/s, the performance improved by 78.9%, while at 3 m/s, the improvement was 17.6%.

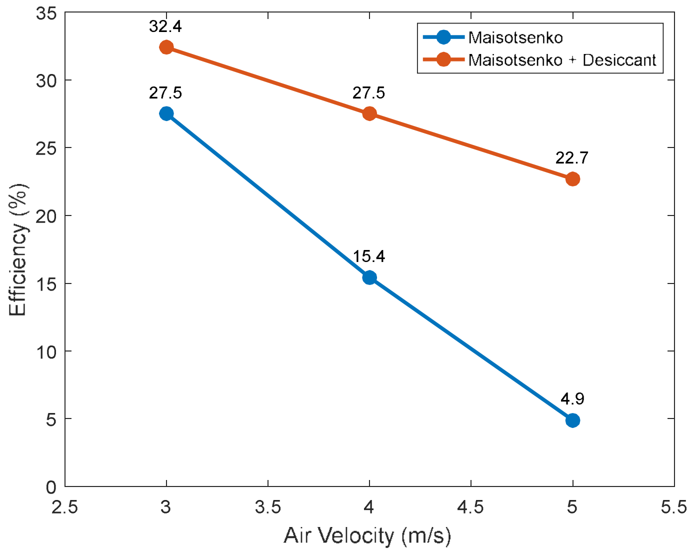

Fig. 9. Dew point temperature efficiency comparison.

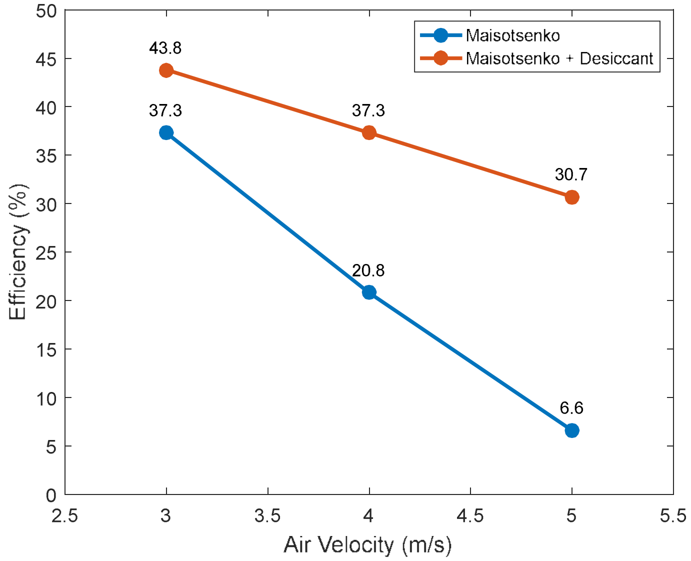

Fig. 10. Wet-bulb temperature efficiency comparison.

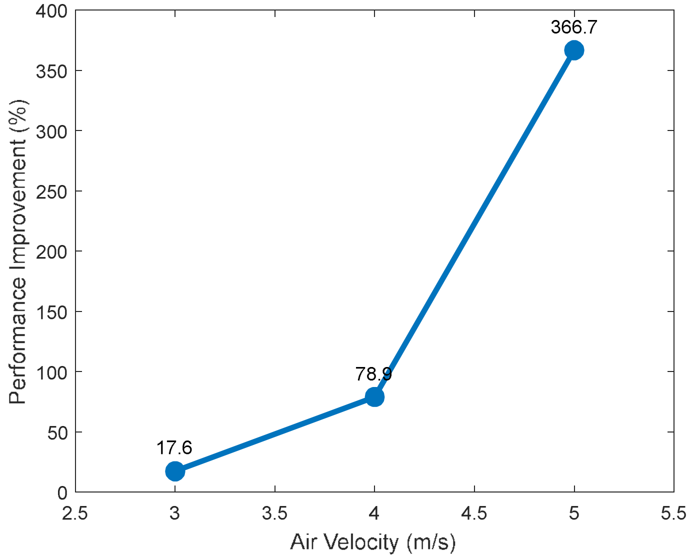

Fig. 11. Peformance improvement.

3.2 Discussion

Previous studies have shown that the Maisotsenko cooling system does not perform optimally in high-humidity environments, a condition commonly found in tropical climates. The desiccant system is a widely used method in air-conditioning cycles to reduce moisture content in the air. In this study, the Maisotsenko system was tested under tropical climatic conditions both with and without the addition of a desiccant system. The objective was to examine the effect of the desiccant integration on the performance of the Maisotsenko system under high humidity.

In the tests conducted without the desiccant, the variation with an air velocity of 3 m/s demonstrated the best cooling performance, with the highest temperature drop, heat transfer rate, and system efficiency. It achieved a temperature drop of 1.7°C, a heat transfer rate of 1.4 W, a dew point temperature efficiency of 27.5%, and a wet-bulb temperature efficiency of 37.3%. Followed by air velocities of 4 m/s and 5 m/s. This is because lower air velocity allows for longer contact time between the air and the wetted surface as well as the separating wall, enhancing the mass transfer during the evaporative cooling process. This is evident in the observed temperature drop and increased humidity of the working air. Similarly, the prolonged air contact improved the heat exchange between the working and product air, resulting in more effective heat transfer.

For the Maisotsenko system integrated with a desiccant, the same trend was observed: the 3 m/s air velocity variation delivered the highest temperature drop, dew-point temperature efficiency, and wet-bulb temperature efficiency with results of 2°C, 32.4%, and 43.8% respectively. This outcome is again attributed to the longer residence time of air at lower velocities, which enhances the evaporative cooling process through better mass and heat transfer. However, the highest heat transfer rate occurred at an air velocity of 5 m/s, reaching 1.9 W, due to the higher mass flow rate, which directly influences the heat transfer rate.

These findings are consistent with those reported by Muzaffar [30], who highlighted the significant influence of inlet air velocity on the efficiency of the Maisotsenko system. The optimal performance observed at an air velocity of 3 m/s in this study confirms that airflow optimization remains essential, even with the incorporation of a desiccant system.

Comparing the performance of the Maisotsenko system with and without the desiccant, it was found that the integration of a desiccant system significantly enhances cooling efficiency. This improvement is due to the reduced humidity of the air entering the Maisotsenko system, resulting from the dehumidification process in the desiccant system. Drier air leads to more effective evaporative cooling on the working air side, which improves heat transfer to the product air and yields a lower product air temperature.

These findings are consistent with the study by Cui *et al.* [19], which stated that the Maisotsenko system performs well in moderate humidity environments but requires additional modifications, such as support systems, to maintain effectiveness under high humidity. The results also support the work of Chen *et al.* [31], who found that evaporative cooling systems need auxiliary systems like desiccants to operate optimally in humid climates. Furthermore, this study complements the findings of Fan *et al.* [17], both of whom noted a decline in Maisotsenko system performance under high humidity conditions. By integrating a desiccant system, this research demonstrates that such limitations can be mitigated, leading to enhanced cooling performance.

4 Conclusions

This research evaluated the performance of a standalone and desiccant-assisted Maisotsenko cooling system under tropical, high-humidity conditions. The main conclusions are: (1) the standalone Maisotsenko cooling system achieves optimal performance at an air velocity of 3 m/s, producing a temperature reduction of 1.7°C, a heat transfer rate of 1.4 W, a dew-point efficiency of 27.5%, and a wet-bulb efficiency of 37.3%; (2) when integrated with a desiccant system, the optimal air velocity remains 3 m/s for maximum temperature reduction and efficiency, achieving a 2°C temperature drop, 32.4% dew-point efficiency, and 43.8% wet-bulb efficiency; (3) the highest heat transfer rate (1.9 W) occurs at 5 m/s due to the increased mass flow rate; (4) the integration of a desiccant significantly enhances cooling performance, with improvements of 366.7%, 78.9%, and 17.6% at air velocities of 5 m/s, 4 m/s, and 3 m/s, respectively; (5) these results confirm the strong potential of desiccant-assisted Maisotsenko systems for high-humidity climates, where conventional evaporative cooling is limited. Future research should focus on building-scale applications, system optimization, and large-scale implementation in tropical environments.

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