

Thermal characteristics enhancement of helical cooling-dehumidifying coils using strips fins

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ABSTRACT

A comprehensive experimental investigation of the performance enhancement of cooling-dehumidifying helical coils using strips fins was conducted. Finned and un-finned coils (base case) were tested at wide ranges of air flow rates, temperatures and humidity at vertical and horizontal orientations. The results showed that (i) for all coil orientations and operating conditions, the finned coil always has better performance (dehumidifying capacity, heat transfer rate, heat transfer coefficient and coil effectiveness) compared to the un-finned coils (ii) placing the coil (finned or un-finned coils) at vertical orientation enhances the coil cooling and humidification capacities, (iii) for the finned and un-finned coils at all orientations, the cooling and humidification capacities increases with increasing the air flow rate, humidity and temperature, (iv) the percentage of increase in the coil performance due to using fins or due to placing it at vertical orientations increases with increasing air flow rate and temperature and (v) the effect of using strip fins on the coil surface is more dominant in case of coil horizontal orientation. Finally the results concluded the recommendation of using finned helical coils at the vertical orientation to maximize cooling and dehumidification capacities and coil effectiveness.

1. Introduction

Process of heat and mass transfer in cooling and dehumidification of moist air in heat exchangers are countered in a lot of engineering applications such as water desalination system and refrigeration and air conditioning systems. Heat transfer process in helical coil heat exchanger had been extensively studied by many researchers, however heat and mass transfer during dehumidification of moist air on striped fins enhanced helical coils has not been studied. The helical coil is an effective device for heat exchange because of its high heat transfer area and heat transfer coefficient in small occupied space. Most of the researches were devoted to compare the heat transfer characteristics of helical coils and straight tubes heat exchangers. Some of these researches were conducted through analytical/numerical studies and other through experimental studies [1–18]. Prabhanjan et al. [1] studied heat transfer in helically coiled heat exchanger compared to straight tube heat exchanger with similar dimensions. Results showed that, heat transfer coefficient increases in helical coils compared to those of straight tubes. Coronel and Sandeep [2] tested two helical coils having different curvature ratios versus straight tube heat exchanger at different flow rates to determine and compare heat transfer capability of the different coils with turbulent flow regimes. Results showed that,

in helical coil heat exchanger the overall heat transfer coefficient is higher than that of the straight tube heat exchanger and it increases with increasing the curvature ratio. Salimpour [3] carried out experimental work to study heat transfer coefficient of shell and helical coil tube with different coil pitches. Results showed that large coil pitches give higher heat transfer coefficient at constant temperature boundary condition. Gupta et al. [4] conducted experiments to develop correlations to be used in the design of finned-coil heat exchangers of air conditioning and refrigeration applications. Experiments were conducted in Reynolds number range 500–1900. Results showed that the predicted correlations can be utilized in heat exchanger design with reasonable accuracy. Mohamed et al. [5] conducted experimental study to determine the condensation heat transfer coefficient of the steam flowing into the helical coil. The different operating factors are pipe diameter, diameter of the coil, pitch coil, and coil directions. The results showed that, the heat transfer coefficient increases when the saturation temperature decreases, the diameter of pipe decreases, the helical-coil diameter decreases, and the coil pitch increases.

Shirgire and Kumar [6] compared between helical coil and straight tube heat exchangers through studying the effect of the heat exchanger geometry on heat transfer and on the heat exchanger effectiveness. The results revealed that the overall heat transfer coefficient increases and

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Nomenclature

A	Heat Transfer Surface area [m ²]
C_p	Specific heat, [kJ. kg ⁻¹ . K ⁻¹]
d	Helical coil diameter [m]
h	Heat transfer coefficient [kW.K ⁻¹ m ⁻²]
C_p	Specific heat, [kJ. kg ⁻¹ . K ⁻¹]
h_{fg}	Heat of evaporation [kJ.kg ⁻¹]
L	Length of coil tube [m]
\dot{m}	Mass flow rate [kg ⁻¹ .s ⁻¹]
Q_l^o	Latent heat transfer rate [kW]
Q_s^o	Sensible heat transfer rate [kW]
Q_t^o	Total heat transfer rate [kW]

RH	Relative humidity of Air
T	Temperature [°C]

Greek symbols

ω	Relative humidity of Air
η_{eff}	Coil effectiveness

Subscript

c	Coil
e	Exit
i	inlet

the effectiveness of the heat exchangers decrease with increasing the flowing fluid velocity. Al-Jabair et al. [7] used three shells and helically coils heat exchangers of different pitches to conduct experimental work to evaluate and compare the heat transfer coefficients for parallel and counter flow. The results showed that, heat transfer coefficient increases with increasing the pitch of the helical coil. Gurav [8] conducted comparative study of heat transfer in helical coil and straight tube heat exchangers. From the results, it was reported that increasing the curvature ratio causes the increase of the heat transfer coefficient. The heat transfer coefficient for helical tube-in-tube arrangement was approximately 10–20 times of the straight tubes arrangement. Ankanna and Reddy [9] performed parametric analysis for straight tube and helical coil heat exchangers. Both tubes were tested for parallel and counter flow configurations. The effects of various parameters on the effectiveness were observed. For helical counter flow arrangement, the overall heat transfer obtained was less than parallel flow arrangement. It was found that the effectiveness of helical coil heat exchanger was always more than that of straight tube and higher values were observed for counter flow configuration. Naphon [10] conducted experiments on helical coil heat exchanger consisting of a shell and helical coil of 30 turns with and without fins for calculating and comparing heat transfer and coils performances. Ghorbani et al. [11,12] experimentally studied the convection heat transfer in helical coil tube at different diameters, pitches of coil and mass flow rates. The results showed that, when the mass flow rate increases the effectiveness of the heat exchanger decreases. Bandpy et al. [13] experimentally studied the effect of the coil pitch on heat transfer from the coil to the shell in helical coil-shell heat exchanger. The tests were conducted for laminar as well as turbulent regime at different flow velocities and temperatures. The results showed that with increasing the coil pitch for the same inside tube diameter, the heat transfer coefficient was found to increase. Nada and Alshaer [14,15] developed correlations for Nusselt number and pressure drop for double tubes and multi tubes in tube helical coils, respectively. Different numerical investigations were recently conducted for multi tubes in tube helical coil heat exchangers to study the effect of the mass flow rates, number of tubes, heat-flux and temperatures on the flow regime and heat transfer coefficient [16–18].

Gore et al. [19] experimentally compared the performance of the straight tube and helical coil heat exchangers. The results were compared with the help of verified CFD model to infer that helical coil gives superior heat transfer rates compared with the straight tube coil. Shriyan [20] conducted a review on heat transfer characteristics of fluids in curved and straight tubes for various parameters and under different experimental conditions. It was reported that, surface geometry modifications like bending of straight tubes into curved coils are effective and efficient method for heat transfer enhancement. Nada et al. [21] used helical coil tube with strips fins to promote heat and mass transfer coefficient during vapor condensation in evaporative cooling system. Gavade et al. [22] conducted experimental comparative analysis between a helical coil and a straight tube heat exchanger for

parallel and counter flow. Based on the results obtained, it was concluded that the helical tube has a larger surface contact area that allows the fluid to contact surface for a longer period and this improves the heat transfer compared to the straight tube. Sreejith et al. [23] also conducted comparative experimental analysis between helical and straight heat exchanger for parallel flow and counter flow arrangements. It was also reported that the overall heat-transfer coefficient and the heat exchanger effectiveness are relatively high compared to the straight tube heat exchanger. Nada [24] conducted numerical and thermodynamic analysis of air cooling-dehumidification/desiccant regeneration processes by a falling liquid desiccant film on finned-tubes for different flow arrangements. Parallel, quainter and cross flow arrangements were investigated to find the best arrangement for the coil performance. Ehsan et al. [25] experimentally studied the effect of different operating parameters of helical coils such as coil pitch, coil diameter, number of turns, and mass flow rater on Nusselt number. The work was done on seventeen helical coils to study the natural convection heat transfer between the coils and the water tank in which the coils were submerged. Nada et al. [26,27] experimentally investigated the performance of the shell and finned and un-finned helical coils heat exchanger to study shell diameter effect and the existence of external fins on the heat transfer process. Four shells of different diameters were tested in this work for finned and un-finned coils.

Heat and mass transfer characteristics of water vapor condensation on/in helical coils were also extensively studied by many researchers. Most of the researches were devoted to determine the condensation heat transfer coefficient in helical coil at different operating parameter by using analytical or experimental investigation [28–30]. Gupta et al. [28] carried out an experimental study of heat transfer and pressure drop characteristics of R-134a condensing inside a helical coil tube in horizontal position with the counter flow of the water in the shell. The effects of the mass flux, amount of vapor, and the evaporative temperature on Nusselt number and pressure losses were studied. Ali and Gulhane [29] conducted experiments on condensation heat transfer in a vertical helical coil of 175 mm coil diameter under variable mass flux conditions. The results were used to evaluate coefficient of heat transfer and compare it with the correlations obtained in previous works in the literature. Yu et al. [30] studied the heat transfer during the condensation of hydrocarbon propane refrigerants in a helical coil. The investigation was carried out at different operating conditions as mass flux and saturated temperature. The effects of flow parameters were analyzed. The result revealed the increase of the heat transfer coefficient with the increase of the mass flow rate and vapour quality.

Several researches have been conducted experimental and analytical investigations to explore the effects of the tilt angle and the surface orientation on the heat and mass transfer coefficient [31–37]. Saffari et al. [31] theoretically and numerically studied stratified condensation heat transfer mechanism in an inclined tube. The heat transfer coefficient for 30° inclination angle was high in comparison with 60° and 90° inclination angles. Nada et al. [32–34] conducted several experimental

studies of the effect of the inclination angle of the heat transfer surface on the heat transfer coefficient. The investigations were done for annular and horizontal fluid layer as well as for heat transfer around semicircular inclined tubes. The results showed that the inclination angle affect heat transfer in the layers. Mozafari et al. [35] investigated the effects of refrigerant mass flux, vapor quality and coil inclination angle of on the condensation and pressure drop processes of R 600a flows in the helical coil oriented at different angles: zero, 30°, 60° and 90°. The study was done at coil diameter, coil pitch, and number of turns of 305 mm, 35 mm, 210 mm and 6, respectively. The results showed that at any inclination angle, when the mass flow rate and vapor quality increase the heat transfer coefficient and pressure drop of condensation process increase. Ewim et al. [36] experimentally studied condensation of R134a in tube at different parameters such as mass flux, saturation temperature, wall tube temperatures and tube inclination angle to find the effect of these parameters on the condensation heat transfer coefficient. William et al. [37] presented an experimental study for steam condensation in inclined flatted tubes used in air-cooled condenser. The inclination angle was varies from horizontal (0°) to 75 °C. The overall heat transfer coefficient was found to be increased by increasing the inclination angle of the tube. Nada and Hussein [38] conducted an experimental work to find a correlation of heat transfer coefficient for steam condensation outside inclined tubes tube in terms of the inclination angle. An experimental and numerical investigation of the effect of the tube curvature on the condensation heat transfer and flow regime for vapor condensing inside horizontal helically coiled tubes was conducted by Naphon and Suwgrai [39]. Three different curvature ratios were tested at constant wall coil temperature. The results were compared between straight tube and helical coil.

1.1. Gap in literature review and aim and innovation of the present study

It is evident from literature review that there is no comprehensive study for air cooling and dehumidification on helical coils of enhanced surfaces. The effects of coil orientations and the existence of strips fins on the coil outer surface on the dehumidification and cooling capacities of the coils for different air flow rates, temperatures and humidity are not exist in the literature. The water condensation/dehumidification on helical coils during air dehumidification exists in a lot of engineering application such as refrigeration, air conditioning and water desalination systems. The aim of the present work is to conduct experimental investigation of the heat transfer and vapor condensation/dehumidification characteristics on helical coils of enhanced surfaces. A parametric study of the effects of helical coil orientation and the air inlet conditions on the coil performance and water condensation rate was also conducted. The effects of adding ribs/wire fins on the external surface of the coil was also investigated by testing two similar coils; one without fins and the second with fins. The study aims to find the geometric, orientation and operating conditions which gives the best performance of the dehumidifying helical coils. The presence of such data will help in designing of helical coils used in the different application of different purposes

2. Experimental procedure and setup

2.1. Experimental setup

The test loop was constructed to investigate the heat transfer and vapor condensation characteristics during air dehumidification on the outer surfaces of finned and un-finned helical coils. The apparatus was constructed to enable conducting such investigations at horizontal and vertical orientations of the coils and at different operating conditions

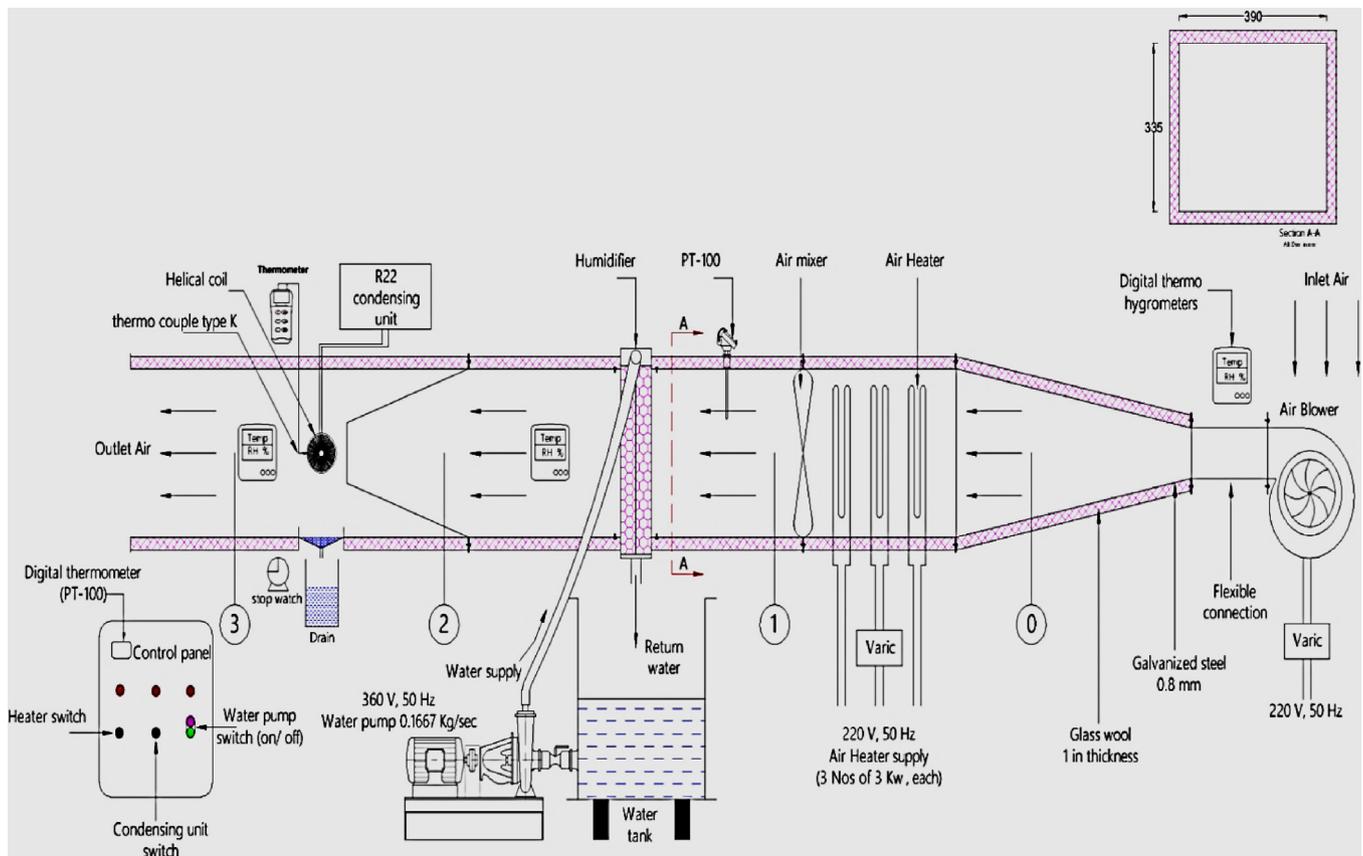


Fig. 1. A schematic diagram of the experimental set up.

(air flow rate, temperature and humidity) for the air required to be dehumidified. The test rig is shown schematically in Fig. 1. The setup consists of four sections: air duct system, condensing unit section, water system for air humidification and helical coils section (test section). The air duct section is an open loop section of 3 m length and having a cross section dimension of 390 mm (width) \times 335 mm (height). Air flows through the duct using air blower with variable speed. The blower is connected to the duct system through a diverging section. The walls of the air duct were thermally insulated using glass wool thermal insulation of thickness 1-inch. The air duct system contains the following sections: electrical heater section, water humidifier section, an air mixing section and helical coil section. The air enters to the duct system is firstly pass on the electric heating section where it can be heated to the required temperature. The air is then passes in the humidification section to raise the humidity of the air. A mixing section was placed after the humidifier to mix the air and ensure uniform temperature and humidity of the air across the test section. The air then passes on the helical coil to dehumidify the air by condensing the water vapor on the surface of the coil.

The electrical heater section consists of 3 electric heaters; each one has a power of 3 kW. The heater was made of 3 m of steel bar of a diameter 8.5 mm and formed in the form of serpentine shape that occupies all the cross section of the air duct. The three electrical heaters were placed in the duct in a staggered arrangement to cover the cross-sectional area of the entire duct to assure uniform heating of the air. The electric heaters were connected to a Variac to smoothly control the power input to the heater and accordingly control the temperature of air to the required one.

The water humidifier consists of two parts; a honeycomb section and a water distribution section. The honeycomb humidifier pad section consists of two layers of vertical honeycomb pad of thickness 70 mm for increasing the humidity of the air. The water distribution section is a horizontal stainless-steel distribution water pipe of 1 in. diameter and has 13-holes of 4 mm diameter uniformly distributed across the air duct section to assure uniform feeding of the pad section with water. The honeycomb structure material is uniformly wetted by continuous dripping of water onto the upper edge of the cooling pad and the water flows from top to bottom of the pad. The water humidifier was designed to cover the entire cross-sectional area of the air duct to ensure uniform moisture distribution for air flowing inside the duct. The water system used to supply water to the humidifier section consists of water pump (360-volt, 50 Hz, 10 Lit/ min), water tank (galvanized steel tank of 0.8 mm thickness, 400 mm height \times 335 mm width \times 390 mm length), electric heater of 1500 Watt connected to a

Variac to heat and control the water to the required temperature and connecting pipes and hose with valves to control the water flow.

DX helical coil with refrigerant R-12 passes inside the helical tube of the coil is used as the test section of the present study. The moist air exits from the humidifier and the mixing section passes on the helical coil to be dehumidified and cooled. The coils are made from thin-aluminum tubes with inner diameter of 8 mm and thickness 0.5 mm. The dimensions of the coils as shown in Fig. 2 are: $d = 8$ mm, $R_c = 80$ mm, $b = 20$ mm, and the number of turns = 24. Finned and un-finned coils were tested. The finned coil contains radial ripped fins on the external surface. The fins are in the form of flat aluminum wire strips fins. The wire strips dimensions are 30 mm \times 2 mm \times 0.5 mm (length \times width \times thickness) with spacing distance between wires of 0.7 mm. Fig. 2 shows the geometric dimensions of the helical coils without fins and with ripped wired fins. The test section was designed to enable placing the helical coil at horizontal or vertical orientations to conduct separate tests were conducted at coil horizontal and vertical orientations.

A condensing unit was used to supply the refrigerant to the helical coil to remove the coil cooling load and maintain the outside surface temperature of the coils at the required low temperature. The model of the unit is Optyma™ Danfoss condensing unit. The main components of the condensing unit are compressor (model SC15G-104G8525), air cooled condenser (ModelBG-4/5-118U0031) and filter drier. The helical coil (test section) was connected to the condensing unit and worked as DX coil. Refrigerant passes inside the condensing unit circuit and the test coil, while the moist air passes over the surface of the helical coil. A basin was place underneath the helical coil to collect and measure the water condensed on the coil surface.

2.2. Measuring devices

Measurement devices were inserted in the test rig to record the measurements required to study the performance of the helical coils and investigate the heat transfer and vapor condensation processes on the helical coils. The measuring instruments used in this study were hygro-thermometer, a graduated vessel, stop watch, PT-100, digital thermometer, thermocouples and clamp multimeter. Fig. 1 shows the locations of the different instruments to conduct these measurements. Three thermocouples of type K were used for measuring the surface temperature of the helical coil. Three hygro-thermometer were used to measure the relative humidity at different locations of the air path. The hygro thermometer combines a hygrometer and a thermometer used to measure the humidity and temperature of air to determine its relative

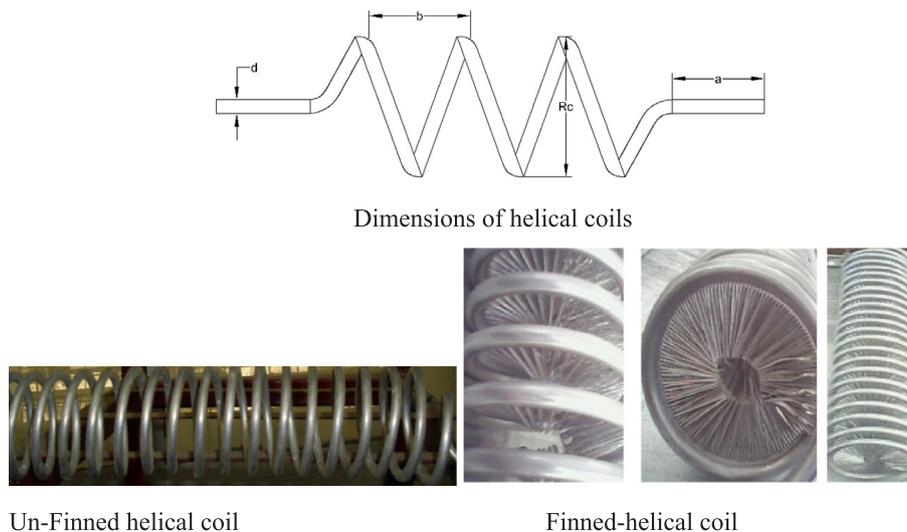


Fig. 2. Dimensions and photos of tested helical coils.

humidity. Two Digital hygro-thermometers are used to measure the RH of the air across helical coil, model HTC-1 measuring range (temperature $-10\text{ }^{\circ}\text{C}$ to $+50\text{ }^{\circ}\text{C}$, accuracy $\pm 0.2\text{ }^{\circ}\text{C}$, temperature resolution $\pm 0.1\text{ }^{\circ}\text{C}$, and humidity range 10%–99% RH, with accuracy $\pm 1\%$ RH), another digital hygro-thermometer is used to indicate RH of the air at ambient condition in laboratory, model SH-109 measuring range (temperature indoor $-10\text{ }^{\circ}\text{C}$ to $+50\text{ }^{\circ}\text{C}$, temperature outdoor $-50\text{ }^{\circ}\text{C}$ to $+70\text{ }^{\circ}\text{C}$, accuracy $\pm 0.2\text{ }^{\circ}\text{C}$, temperature resolution $\pm 0.1\text{ }^{\circ}\text{C}$, and humidity range 20%–99% RH, with accuracy $\pm 1\%$ RH). PT-100 sensors (platinum resistance thermometer) were used to measure the air temperature before and after each section (air heater, humidifier, and helical coil) of the air duct section. PT100 is connected to a digital thermometer to record the measured temperature model (TC4Y). A clamp meter is used for measuring current on a wire which used it for measuring current inlet to the condensing unit and to the electric heater. The water condensed on the helical coil surface was collected and measured by a graduated vessel with minimum division of 10 ml. using stop watch for measure the time of water collection.

2.3. Experimental conditions

The heat transfer and air dehumidification characteristics and performance of the coils were investigated by doing experiments under the following experiments conditions and parameters:

Air flow rate range	0.04–0.17 [kg.s ⁻¹]
Water flow rate entering to humidifier	0.1667 [kg.s ⁻¹]
Air temperature exit from the electric heater T1,	55, 60, 65, 70, 75 °C
Air temperature range at the inlet of the test coil	32–38 °C
Air humidity at the inlet of the test coil	24–32 [g.v.kga ⁻¹]
Water temperature entering the humidifier	31 °C

The experiments were done on two different types of helical coils (coil without fins and coil with ripped-wire fins). The experiments on each coil were conducted at different orientations of the coil (horizontal and vertical position). For each coil and at each orientation different experiments were conducted at the different above mentioned conditions.

2.4. Data reduction

The water dehumidification and vapor condensation rates on the coil surface, heat transfer between the air and the coil, heat transfer coefficient between the air and the coil and coil efficiency were calculated for each experiment from the measurements of the experiment. Eqs. (1)–(7) are used to calculate these quantities for each experiment. The performance and the heat transfer characteristics of the helical coil were investigated by studying and solving these equations (Eqs. (1)–(7)) using Engineering Equation Solver (EES) software.

The rate of vapor condensation from the air on the surface of the coil was calculated by measuring the amount of water condensed on the coil surface during a period of time. The water condensation rate can be also calculated from the different measurements using Eq. (1)

$$\dot{m}_{\text{water}} = \dot{m}_{\text{air}} \times (\omega_{i,\text{coil}} - \omega_{e,\text{coil}}) \quad (1)$$

where \dot{m}_{water} is rate of water condensate on the coil, \dot{m}_{air} is the air flow rate on the coil duct section, $\omega_{i,\text{coil}}$ and $\omega_{e,\text{coil}}$ are the specific humidity at the inlet and exit of the helical coil, respectively. The water condensation rate calculated from Eq. (1) was within $\pm 5\%$ of the measured one. In the analysis of the results, the water condensation rate was taken from the measurements of the condensation rate and is not taken from Eq. (1)

The sensible, latent and total heat transfer rate between the air and the coil surface were calculated from Eqs. (2)–(4), respectively

$$Q_s = \dot{m}_{\text{air}} \times C_{p,\text{air}} (T_{i,\text{coil}} - T_{e,\text{coil}}) \quad (2)$$

$$Q_1 = \dot{m}_{\text{water,condensation}} \times h_{fg} \quad (3)$$

$$Q_t = Q_s + Q_1 \quad (4)$$

where Q_s , Q_1 , and Q_t are the sensible, latent, and total heat transfer rate between the air and the coil, respectively. $C_{p,\text{air}}$ and h_{fg} are the specific heat of air and the latent heat of water, respectively. $T_{i,\text{coil}}$ and $T_{e,\text{coil}}$ are the air temperature at the inlet and exit of the helical coil, respectively. The condensation heat transfer coefficient was calculated from Eq. (5)

$$h_T = Q_T / [A_c \times (T_{i,\text{coil}} - T_{\text{surface coil}})] \quad (5)$$

where h_T is the total heat transfer coefficient, respectively. A_c is the surface area of the helical coil ($\pi d L$) where d is the diameter of helical coil, and L is the tube length. $T_{\text{surface coil}}$, $T_{i,\text{coil}}$ are the surface coil temperature and air temperature entering to the coil section, respectively.

The helical coil effectiveness (η_{eff}) is calculated from eq.6

$$\eta_{\text{eff,coil}} = (T_{i,\text{coil}} - T_{e,\text{coil}}) / (T_{i,\text{coil}} - T_{\text{surface coil}}) \times 100\% \quad (6)$$

2.5. Uncertainty analysis

Eqs. (1)–(6) can be considered on the form $y = f(x_1, x_2, x_3, \dots, x_n)$ where y can be considered as h , Q , m or η_{eff} and $(x_1, x_2, x_3, \dots, x_n)$ are the measured parameters that affect the calculation of y according to Eqs. (1)–(6). The measurement errors of these parameters are ± 0.2 for any temperature measurements, $\pm 0.5\%$ for any humidity measurements, ± 0.01 L for measurements of volume of condensate water, ± 0.01 s for time measurements and ± 0.0005 kg.s⁻¹ for measurements of air mass flow rate. The uncertainty in the calculation of y due to the different errors in the measurements of the different physical quantities $(x_1, x_2, x_3, \dots, x_n)$ can be calculated from Eq. (7) [40]

$$\frac{\Delta y}{y} = \left[\left(\frac{\partial y}{\partial x_1} \frac{\Delta x_1}{y} \right)^2 + \left(\frac{\partial y}{\partial x_2} \frac{\Delta x_2}{y} \right)^2 + \dots + \left(\frac{\partial y}{\partial x_n} \frac{\Delta x_n}{y} \right)^2 \right]^{1/2} \quad (7)$$

where $\frac{\partial y}{\partial x_i}$ was calculated by analytical differentiation at the measurements values. The minimum and maximum uncertainty in calculating the condensate mass flow rate, the heat transfer rate, the heat transfer coefficient and the coil effectiveness were calculated to be (2.9 and 5.3%), (3.05, 5.34%), (3.45% and 6.03%) and (3.7 and 5.65%), respectively.

3. Results and discussions

The results of this work are presented to investigate and compare the heat transfer and the air dehumidification/water condensation characteristics for the finned and the un-finned helical coils placed at different (vertical and horizontal) orientations. The investigation and comparisons are conducted for different operating conditions: air flow rate, air inlet temperature and air inlet humidity. For the sake of the investigation and comparison studies, the effects of the different parameters such as air temperature, air humidity, air flow rate, helical coil orientations and the existence of the fins on the helical coil performance were presented in details. The coil performance was measured in terms of the heat transfer rate, heat transfer coefficient, the water dehumidification/condensation rate and the coil effectiveness.

3.1. Effect of air flow rate

Figs. 3–6 show the effect of the air flow rate on the coils performance: water condensation rate, heat transfer rate, heat transfer coefficient and coil effectiveness, respectively for the finned and un-finned coils at the vertical and horizontal orientations of the coil for air temperatures $70\text{ }^{\circ}\text{C}$ as an example; curves of other air temperature have the same trend and were omitted for the allowable limited numbers of figures in the paper. Fig. 3 shows that for the finned and un-finned coils

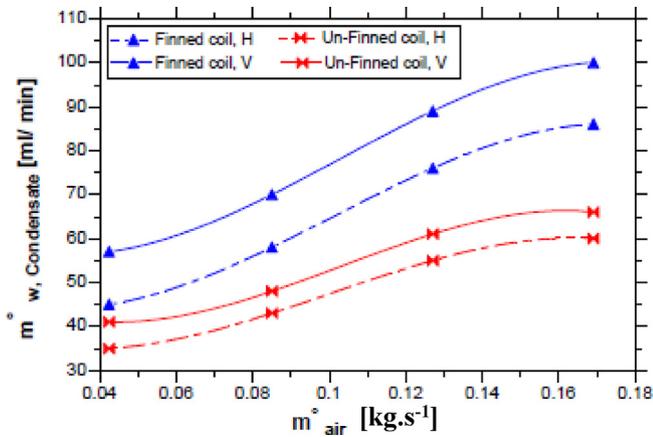


Fig. 3. Effect of air flow rate on the dehumidification capacity of the finned and un-finned coils at the horizontal and vertical orientations ($T_{1,air} = 70\text{ }^{\circ}\text{C}$).

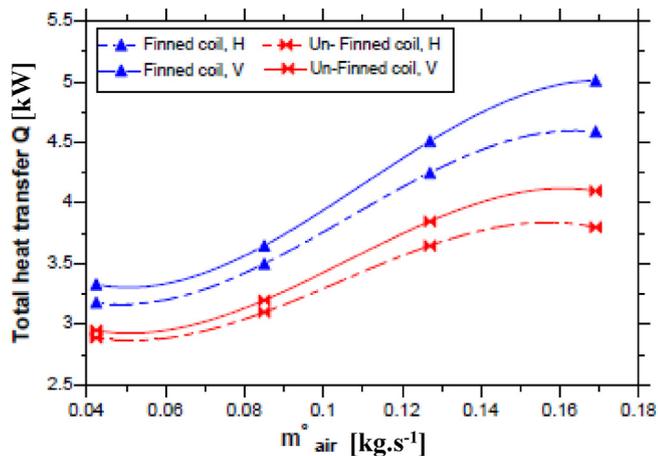


Fig. 4. Effect of air flow rate on the heat transfer rates of the finned and un-finned coils at the horizontal and vertical orientations ($T_{1,air} = 70\text{ }^{\circ}\text{C}$).

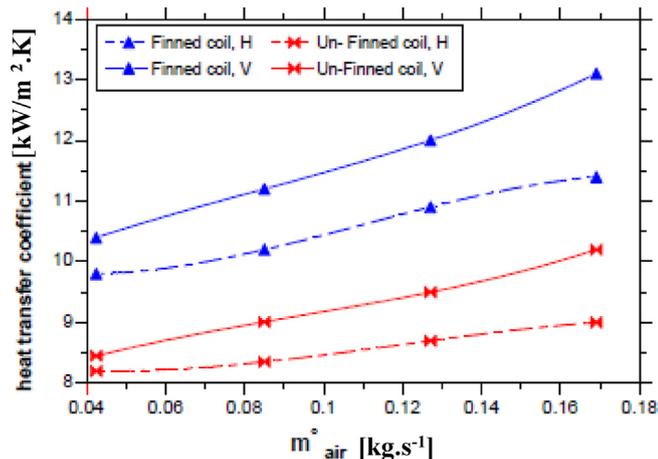


Fig. 5. Effect of air flow rate on the heat transfer coefficients of the finned and un-finned coils at the horizontal and vertical orientations ($T_{1,air} = 70\text{ }^{\circ}\text{C}$).

at the horizontal and vertical orientations, the water condensation rate increases with the increase of the air flow rate. The trend of the variation was noticed to be the same for any inlet air temperature and inlet air humidity. The trend of this variation is attributed to (i) the increase of the heat and mass transfer rates between the air and the coil surface with increasing the air flow rate, (ii) the increase of the process of renew of air that in contact with the coil surface with increasing the air

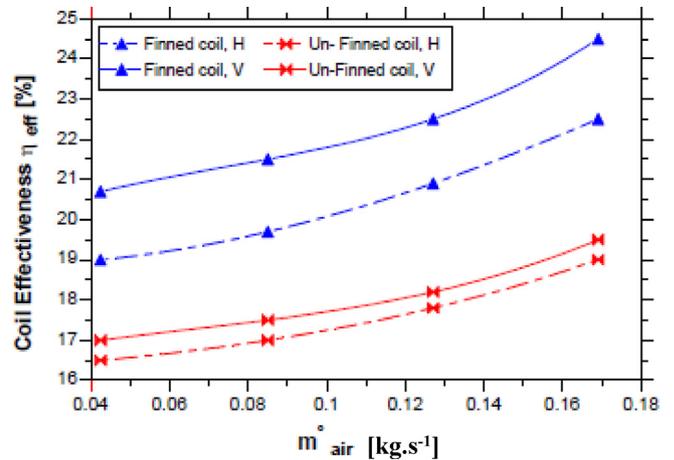


Fig. 6. Effect of air flow rate on the coil effectiveness of the finned and un-finned coils at the horizontal and vertical orientations ($T_{1,air} = 70\text{ }^{\circ}\text{C}$).

flow rate, and (iii) increasing the air flow rate increases the water condensation rate on the coil surface as per Eq. (1). This trend of variation is the same trend obtained by Huzayyin et al. [41] for air cooling and dehumidification on a wavy-finned straight tubes coil.

Figs. 4 and 5 show the increase of the heat transfer rates and the heat transfer coefficient with increasing the air flow rate. The trend is the same for the finned and un-finned coils and at any coil orientation and air inlet temperature. The increase of the total heat transfer with the air flow rate is attributed to the increase of the water condensation rate with the air flow rate as shown in Fig. 3 which leads to the increase of the latent heat transfer and accordingly to the total heat transfer as illustrated in Eq. (6). Fig. 6 shows the increase of the coil effectiveness with the flow rate of air. This can be attributed to the increase of the heat transfer coefficient which leads to the increase of the heat transfer rate which causes more reduction of the air outlet temperature and consequently the increase of the coil effectiveness as given by Eq. (7).

Fig. 7 compares the rates of the sensible and latent heat transfers for the un-finned as an example at air inlet temperature of 50 °C and different air flow rate and coil orientations. The comparison result is the same for the finned and un-finned coils at the vertical and horizontal orientations and at any air. The figure shows that the sensible heat transfer is relatively low compared to the latent heat. This may be attributed to the wet condition of the coil surface and the high condensation rate on the coil surface which leads to covering the coil surface with thick condensate film which make as a resistance of sensible heat transfer. Fig. 7 also shows that the sensible heat is

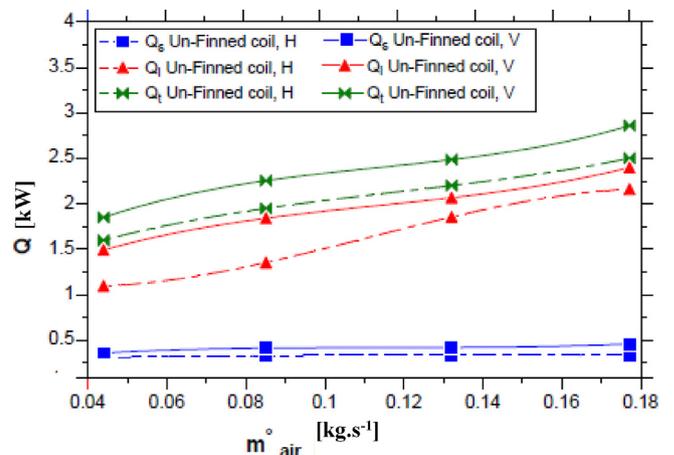


Fig. 7. comparison between sensible and latent heat transfers at the horizontal and vertical orientations.

approximately constant with the air flow rate. This can be attributed to the bypass and contact factor of the coil. The amount of air that in contact with the coil surface is approximately constant whatever the air flow rate and the extra air is bypassed across the coil.

3.2. Effect of air inlet temperature

The effect of the air temperature at the coil entrance on the coil performance: Water condensation rate, heat transfer rate, heat transfer coefficient and the coil effectiveness are shown in Figs. 8–11 for the finned and un-finned coils at different coil orientations air flow rate of 0.085 kg.s^{-1} as an example; curves at other air flow rates have the same trend and are not presented for the allowable limits of the number of figures in the paper. Fig. 8 shows that the water condensation rate increases with increasing the air temperature at coil entrance. This increase may be attributed to (i) the rise of the water vapor pressure in the air with the increase of air temperature which cause the increase of the potential difference of the mass transfer leading to the increase of the vapor mass transfer from the air to the cooling coil surface, (ii) the increase of the air humidity at the saturation condition of the air with increasing the air temperature which leads to high vapor transfer from the air to the coil surface, and (iii) the increase of the heat transfer rate from the coil to the air with increasing the temperature difference between the coil surface and the air leads to the increase of water condensation rate on the coil surface.

Figs. 9 and 10 show that the heat transfer rate and the heat transfer coefficient increases with the increase of the air temperature. This may be attributed to (i) increasing the temperature difference between the air and the coil surface with increasing the air inlet temperature which leads to the increase of the heat transfer rate and consequently the heat transfer coefficient, (ii) the increase of the water condensation rate with increasing the air inlet temperature as shown in Fig. 8 and this leads to the increase of the latent heat transfer.

Fig. 11 shows that the coil effectiveness increases with increasing the air temperature and this can be attributed to the increase of the heat transfer rate and heat transfer coefficient which leads to lower air temperature reduction across the cooling coil which means the increase of the coil effectiveness.

3.3. Effect of air humidity

Figs. 12–15 demonstrates the effect of humidity of air on the coil performance; namely the dehumidification capacity, heat transfer rate, heat transfer coefficient and the coil effectiveness. As show in Fig. 12, increasing the air humidity of the air increases the dehumidification capacity of the finned and un-finned coil. The trend of the effect is the same whatever the coils orientation and the air flow rate and air temperature. The increase of the dehumidification capacity with increasing humidity of air is attributed to the vapor pressure that increases with the increase of the humidity which leads to the tendency of the vapor to transfer from the air to the coil surface leading to more water condensation rate. Figs. 13–15 shows the increase of the heat transfer rate, heat transfer coefficient and the coil effectiveness with the increase of the air humidity. The trend is the same for all coils at the vertical and horizontal orientations and at all air flow rates and air temperatures. This trend of variation can be attributed to the high water condensation rate with the high air humidity which leads to the increase of the latent and total heat transfer and the heat transfer rate and the coil effectiveness.

3.4. Comparison between the finned and un-finned helical coils

Figs. 3–15 compare between the performance of the finned and un-finned helical coils for different coil orientations and at different air flow rates, humidity and temperatures. Figs. 3 and 8 show that the finned helical coil gives higher water dehumidification/condensation

rate than the un-finned helical coil. The trend is the same whatever the coil was vertically or horizontally oriented and whatever the air inlet temperatures and air flow rates. For example, the existence of the fins increases the water condensate rate from 90 ml.min^{-1} (1.5 g.s^{-1}) to 111 ml.min^{-1} (1.84 g.s^{-1}) in case of vertical coil at air flow rate and air temperature of 0.169 kg.s^{-1} and $75 \text{ }^\circ\text{C}$, respectively. The higher dehumidification capacity of the finned helical coil compared to the un-finned coil can be returned to (i) the existence of fins on the coil surface increases the heat and mass transfer surface areas which leads to higher heat transfer rates and water condensation rates, and (ii) the existence of the wire strips fins on the coil surface increase the drainage rate of water droplets from the coil surface and this decreases the condensate film thickness on the coil surface which leads to the increase of the heat transfer rate and consequently the water condensate rate.

Figs. 4 and 9 and Figs. 5 and 10 show that the existence of fins on the coil surface increase the rate of the heat transfer and the heat transfer coefficient where the figures show that the finned coil has higher heat transfer rates and heat transfer coefficient compared to the un-finned coil. For example the total heat transfer rate increased from 4.7 to 5.9 kW and the heat transfer coefficient increased from 10.2 to 13.1 kW.m^{-2} due to the existence of fins in case of vertical orientation and at air flow rate and air temperature of 0.169 kg.s^{-1} and $75 \text{ }^\circ\text{C}$. The trend is the same for the different coil orientation and the air flow rates and air temperatures. The increase of the heat transfer rates and the heat transfer coefficient due to the existence of the fins can be attributed to (i) the increase of the heat transfer and water condensation surface area with the existence of fins, (ii) the decrease of the resistance of heat transfer as the fins leads to higher water drainage rate from the coil surface which leads to lower thickness of the condensate film on the coil surface, and (iii) the existence of fins increases the turbulence level around the coil surface which leads to higher heat transfer rates.

Figs. 6 and 11 compare the coil effectiveness for the finned and un-finned coils for the different coil orientations and different air flow rates and air temperature. The figures show that for the vertical and horizontal coil orientations and at any air flow rates and air temperatures, the effectiveness of the finned coil is always higher than that of the un-finned coil. For example in case of the vertical orientation and at air flow rate and air temperature of 0.169 kg.s^{-1} and $75 \text{ }^\circ\text{C}$ respectively, the coil effectiveness increases from 19.85% to 22%. The increase of the coil effectiveness with the existence of fins can be attributed to the increase of the dehumidification rate, heat transfer rate and the heat transfer coefficients which lead to higher air temperature drop across the coil.

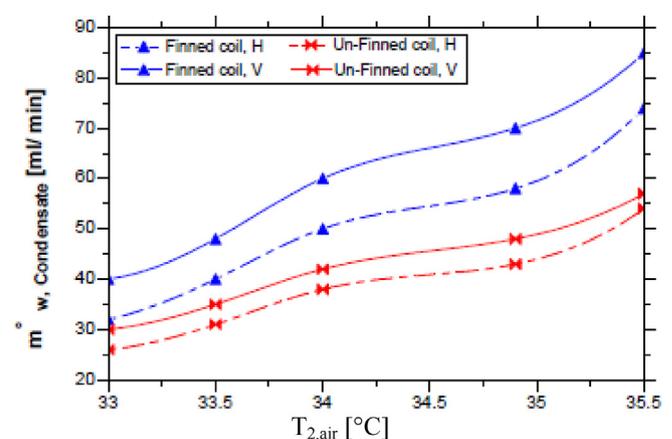


Fig. 8. Effect of air temperature on the dehumidifying capacity of the finned and un-finned coils at the horizontal and vertical orientations ($m^{\circ}_{\text{air}} = 0.085 \text{ kg.s}^{-1}$).

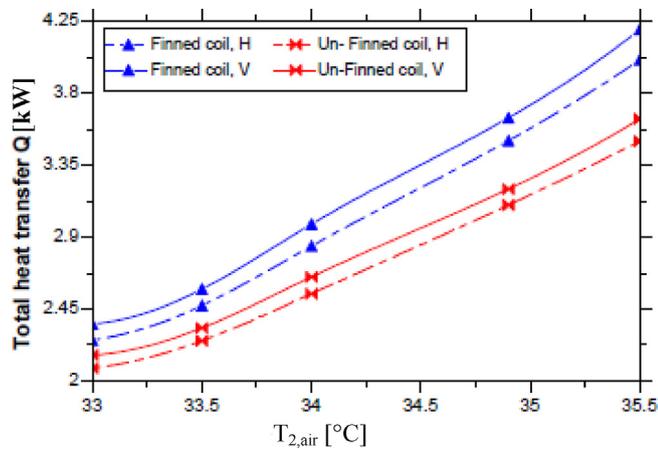


Fig. 9. Effect of air temperature on the heat transfer rates of the finned and un-finned coils at the horizontal and vertical orientations ($m^{\circ}_{air} = 0.085 \text{ kg.s}^{-1}$).

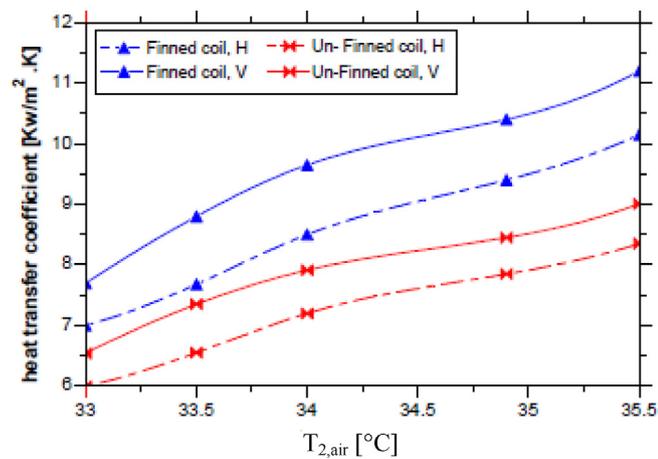


Fig. 10. Effect air temperature on the heat transfer coefficient of the finned and un-finned coils at the horizontal and vertical orientations ($m^{\circ}_{air} = 0.085 \text{ kg.s}^{-1}$).

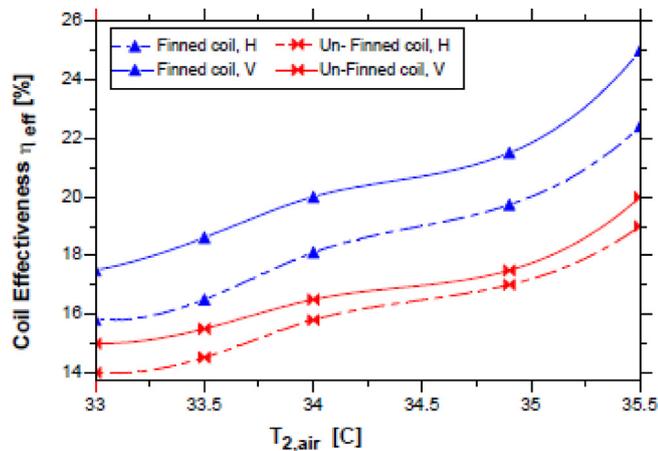


Fig. 11. Effect of air temperature on the effectiveness of the finned and un-finned coils at the horizontal and vertical orientations ($m^{\circ}_{air} = 0.085 \text{ kg.s}^{-1}$).

3.5. Effect of coil orientation

Figs. 3–11 shows the effect of the coil orientation on the performance of the finned and un-finned helical coils for the different air flow rates and temperatures. Figs. 3 and 8 show that the vertical orientation of the coil always gives higher water condensation rate compared to the

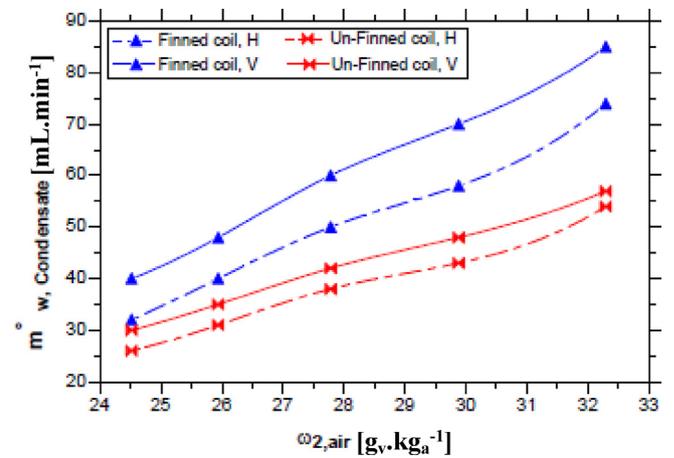


Fig. 12. Effect air humidity on the dehumidifying capacity of the finned and un-finned coils at the horizontal and vertical orientations ($m^{\circ}_{air} = 0.085 \text{ kg.s}^{-1}$).

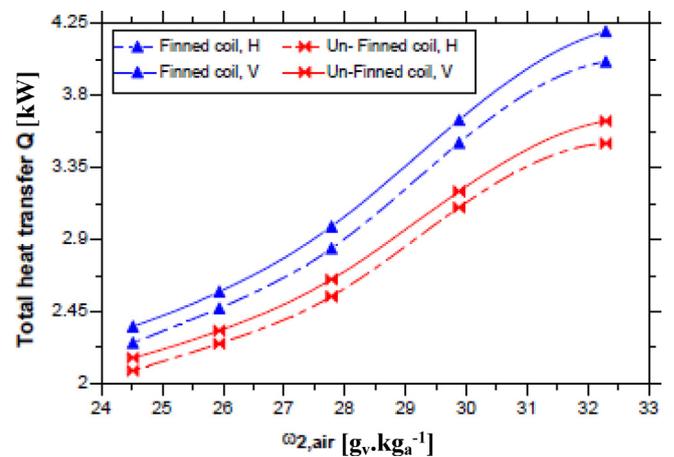


Fig. 13. Effect air humidity on heat transfer rate of the finned and un-finned coils at horizontal and vertical orientations ($m^{\circ}_{air} = 0.085 \text{ kg.s}^{-1}$).

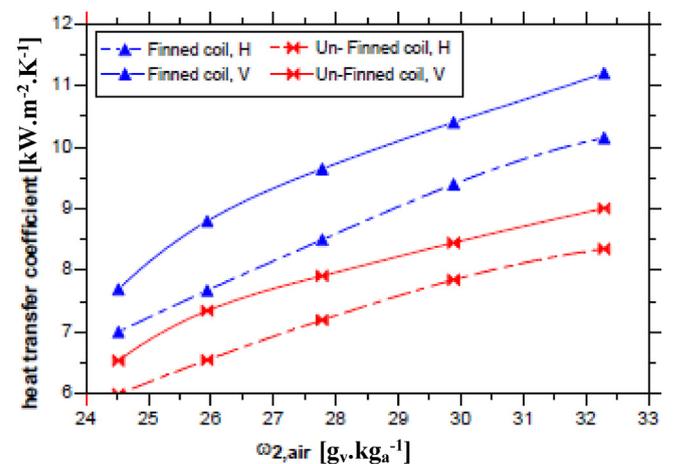


Fig. 14. Effect air humidity on heat transfer coefficient of the finned and un-finned coils at horizontal and vertical orientations ($m^{\circ}_{air} = 0.085 \text{ kg.s}^{-1}$).

horizontal orientation. The trend is the same whatever the coil was finned or un-finned and at all air inlet temperatures and flow rates. For example the water condensation rate increased from 60 ml. min⁻¹ to 66 ml. min⁻¹ and from 105 ml.min⁻¹ to 110 ml.min⁻¹ when the orientation of the un-finned and finned coils changed from the horizontal and vertical orientation at air flow rate and air temperature of

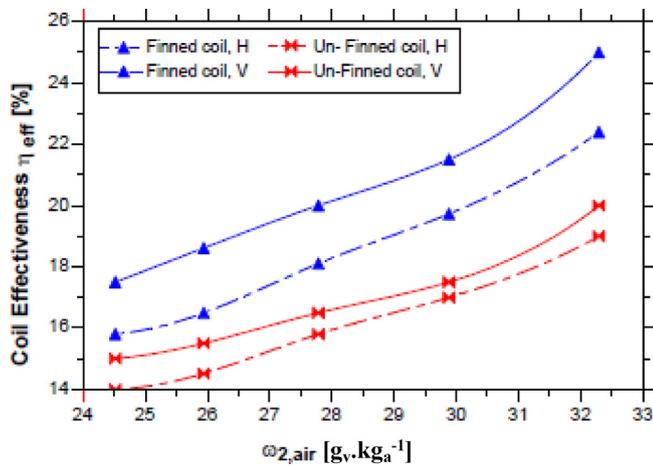


Fig. 15. Effect air humidity on coil effectiveness of the finned and un-finned coils at horizontal and vertical orientations ($m_{\text{air}}^{\circ} = 0.085 \text{ kg}\cdot\text{s}^{-1}$).

$0.169 \text{ kg}\cdot\text{s}^{-1}$ and $75 \text{ }^{\circ}\text{C}$, respectively. The higher dehumidification capacity of the vertical orientation of the helical coil can be attributed to the length of the path of the condensate film/droplets until it separate the coil surface. In the vertical position the droplet moves vertically downward without slides along the longitudinal direction of the coil tube; so the longest path of the condensate droplet is $\pi d/2$. In the horizontal orientation of the coil, the condensate droplets can slide along the longitudinal direction of the coil tube during its vertical movement; so the longest path of the condensate droplet in this case is $\pi d/2$. This means that the vertical orientation of the coil have shortest condensate droplet path until its separation from the coil surface. This makes the rate of condensate removal from the coil surface in case of vertical coil is higher than the horizontal coil. Moreover, the shorter of the condensate path of the vertical orientation means thinner condensate film thickness on the coil surface which leads to higher heat transfer rate and higher condensation rate.

Figs. 4 and 9 and Figs. 5 and 10 show that the vertical orientation of the coil has higher heat transfer rate and heat transfer coefficient comparing the horizontal orientation of the coil. The trend is the same for the finned and un-finned coil and for the different air flow rates and air temperatures. For example the total heat transfer rate and the heat transfer coefficient for finned coil increases from 5.25 kW and $11.5 \text{ kW}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ to 5.9 kW and $13 \text{ kW}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ due to changing the coil orientation from horizontal to vertical orientation at air flow rate and air temperature of $0.169 \text{ kg}\cdot\text{s}^{-1}$ and $75 \text{ }^{\circ}\text{C}$. The increase of the heat transfer rate and the heat transfer coefficient with changing the coil orientation from the horizontal to the vertical can be attributed to the shorter condensate film path and the thinner condensate film on the coil surface in case of vertical orientation of the coil which reduces the heat transfer resistance and increases the heat transfer rate and the heat transfer coefficient.

Figs. 6 and 11 compare the coil effectiveness for the vertical and horizontal orientations of the finned and un-finned coils for the different air flow rates and air temperatures. The figures show that the vertical orientation has higher effectiveness than the horizontal coil orientations for the finned and un-finned coil and at any air flow rates and air temperatures. For example, at air flow rate and air temperature of $0.169 \text{ kg}\cdot\text{s}^{-1}$ and $75 \text{ }^{\circ}\text{C}$, the coil effectiveness of the finned and un-finned coils increase from 19% and 23.5% to 22% and 28%, respectively when the orientation of the coil changed from horizontal to vertical orientation. The increase of the coil effectiveness in case of vertical orientation can be attributed to the increase of the heat transfer rates and the heat transfer coefficients which lead to higher air temperature drop across the coil.

4. Conclusion

The characteristics and performance of the dehumidifying helical coils were experimental investigation for un-finned and strips wired finned helical coils placed at vertical and horizontal orientations. The investigations were conducted at a wide range of air flow rates, air temperatures and air humidity. The coil performance was measured and evaluated in terms of the dehumidification capacity, heat transfer rate, heat transfer coefficient and coil effectiveness. The results analyses revealed that

- The performance (dehumidifying capacity, heat transfer rate, heat transfer coefficient and coil effectiveness) of the helical coil with strips wire fins is higher than that of the un-finned coils at all coil orientations, air flow rates and air properties.
- The vertical orientation of the helical coils (finned or un-finned coils) enhances the coil performance and the system productivity compared with the horizontal orientation for the entire range of the air flow rate and air properties.
- The coil dehumidification capacity and the coil performances increases with the increase of the air flow rate, air temperature and air humidity. The trend is the same for finned and un-finned coils at the vertical and horizontal orientations.
- The percentage of increase in the coil performance due to using fins increases with increasing the air flow rate and the air temperature.
- The effect of using strip fins on the coil surface is more dominant in case of horizontal orientation of the coil compared to the vertical orientation.

Finally the study concluded the recommendation of using finned helical coils at the vertical orientation for optimal performance of the dehumidifying coil in HDH system.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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