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The Effect of Air Velocity in Liquid Desiccant Dehumidifier Based on Two Phase Flow Model Using Computational Method

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Abstract: *The main challenges of the engineers in the air conditioning field are the environmental hazardous due to CFC and power consumption of the system. The liquid desiccant air conditioning system which could deal with the latent load independently with desiccant absorption has been regarded as an environmental friendly and energy saving alternative. The falling film liquid desiccant air conditioning system is promising to achieve a low pressure drop and low possibility of solution droplet carried out by air. This paper studied the effect of velocity of air on the heat and mass transfer in the falling film type liquid desiccant dehumidifier. The simulation has been conducted on two dimensional simple two phase model with the help of the CFD software "FLUENT". The volume of fluid (VOF) method has selected for this two phase flow analysis. The involvements of gravity, viscosity and surface tension have not been neglected in this study. For the better prediction of heat and mass transfer process the penetration mass transfer theory has been employed. The result shows the importance or critical role of the air velocity on dehumidification process in the liquid desiccant dehumidifier.*

Keywords: *Liquid desiccant dehumidifier, CFD, volume of fluid, two phase flow.*

1. INTRODUCTION

Environmental and economical problems associated with conventional vapour compression air conditioning systems have significantly increased the use of desiccant based air conditioning systems as a replacement. Nevertheless, desiccant air conditioning is only used in some specific applications, such as super markets, hospitals and applications where very dry supply air conditions are required, often in very humid Climates.

There are lots of work have been carried out in the liquid desiccant dehumidifier experimentally and numerically. The both studies proving that the liquid desiccant dehumidifier system is a cost effective and efficient technology in the air conditioning area. The works [1] – [7] explaining the importance of parameter selection like, dehumidification and regeneration temperature of liquid desiccant, liquid velocity, desiccant concentration etc. The Yonggao Yin et al. introduced the waste heat utilization for the regeneration of liquid desiccant. And these all works have done on packed bed type system. The few papers are for the falling film type system; in these papers most of the works are making the good agreement with the previous results. J. Patek and P.T. Tsilinginiris were evaluated the properties of liquid desiccant and moist air. The balance works are showing the computational and numerical methods to study the performance of the liquid desiccant dehumidifier, in which selection of Volume of fluid method for multiphase flow also described.

Here the liquid desiccant temperature has maintained between 22^0C and 27^0C, [1] because beyond these temperatures the liquid desiccant may loses the ability to dehumidify the air. From the different liquid desiccants, the properties [11] of the LiCl are much suitable for the better dehumidification. Natan Padoin et al. [19] studied the Heat and mass transfer modelling for multi component multiphase flow with CFD. These phenomena are encountered in systems comprised of two or more phases, in which at least one of them is a mixture of many chemical species. The predictability of such multiphase and multi component systems plays a major role in the efficient design and operation of equipment and processes, where CFD has been frequently applied successfully over the past decade. Modelling multicomponent flow remains a challenge in relation to both micro and macro systems.

1.1. Scope of the Present Work

Study the effect of air velocity on heat and mass transfer process and based on the study predict the performance of the falling film type liquid desiccant dehumidifier

- The computational method (VOF) has been used for the study
- The Licl solution with wt 30% has been fixed as the liquid desiccant based on the literature survey for the better result.

2. MODELING AND FORMULATION

2.1. Problem Description

To do the simulation of parametric study, the counter flow configuration is chosen and which is most popular for liquid desiccant dehumidifier. The simulation is conducted for the unsteady two-phase flow with free liquid surface in the channel between two flat plates. The simplified geometric construction is presented in Fig.1. The length of the plates is 150 mm and the distance between the plates is 20 mm. The liquid desiccant solution is supplied to the plate through the upper-left hole while the moist air is introduced by the bottom-right hole. In this way, the liquid and gas flow counter-currently.

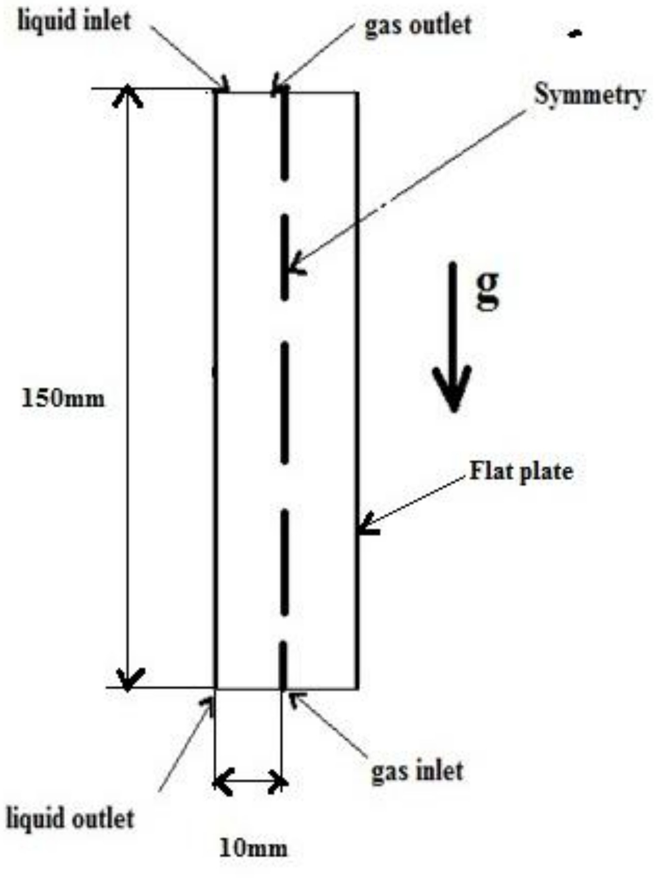

Fig1. *Schematic of the simplified physical model*

2.2. Governing Equations

Though the temperature and velocity are involved, it is to consider the three conservation equations. In this case the study is conducting on multiphase flow, so it is important to choose the suitable model for the simulation. There are mainly four type of multiphase flow models Discrete phase model, Eulerian model, Mixture model and Volume-of-Fluid (VOF) model. If two fluids are mixed together in a macroscopic level then it is a multiphase flow, here the fluids are liquid desiccant and air. For multiphase flow there is an identifiable boundary between two phases, so we have to indicate to the solver how this boundary performs may be a typical droplet size or a free surface. For the typical droplet size the mixture model is preferred and for free surface the volume of fluid model is preferred. Here the immiscible desiccant film separated by a clearly defined interface so the volume of fluid model has been chosen.

VOF Model

For the gas–liquid two-phase system, the mass and momentum conservation equations are based on the volume fractions of the gas and liquid. The properties r density and µ viscosity in each computational cell are represented by,

$$\rho = \alpha_l \rho_l + \alpha_a \rho_a \tag{1}$$

$$\mu = \alpha_l \mu_l + \alpha_a \mu_a \tag{2}$$

If the liquid phase is set as the secondary phase of the VOF model, the movement of the phase interface will be decided by al, which is the volume fraction of the liquid phase. The relationship of the value and the state of the cell is,

If $\alpha_l = 1$ The cell is full of the liquid

$0 < \alpha_l < 1$ The cell containing the interface between the liquid and the gas

$\alpha_l = 0$ The cell is empty of the liquid

Thus, the interface between the gas and liquid can be tracked by solving the following continuity equation for the volume fraction,

$$\frac{\partial \alpha_l}{\partial t} + u.\nabla \alpha_l = 0 \tag{3}$$

Then, the volume fraction for the gas will be achieved by the equation,

$$\alpha_l + \alpha_g = 1 \tag{4}$$

The solution method is similar when choosing the gas phase as the secondary phase in the VOF model.

Mass conservation equation

$$\frac{\partial \rho}{\partial t} + \nabla(\rho u) = 0 \tag{5}$$

Momentum Conservation Equation

$$\frac{\partial(\rho u)}{\partial t} + \nabla.(\rho u u) = -\nabla P + \nabla.\left(\mu(\nabla u + \nabla u^T)\right) + \rho g \tag{6}$$

Energy Equation

$$\frac{\partial(\rho E)}{\partial t} + \nabla.\left(u(\rho E + P)\right) = \nabla.\left[k\nabla T - \sum h_k J_k\right] + S_E \tag{7}$$

Where S_E is the energy source term. The definition of the average energy E is as follows,

$$E = \frac{\sum_{q=1}^{n} \alpha_q \rho_q E_q}{\sum_{q=1}^{n} \alpha_q \rho_q} \tag{8}$$

And Eq is obtained according to the specific heat and the temperature of the qth phase.

Species Transport Equations

$$\frac{\partial}{\partial t}(\alpha_q \rho_q x_{k,q}) + \nabla.(\alpha_q \rho_q u x_{k,q} - \alpha_q \Gamma_{k,q} \nabla x_{k,q}) = S_{jg,k} \tag{9}$$

q=1,…, n k=1,….., m

$$S_{jg,k} = K_g(W_{gb} - W_{ge})A \tag{10}$$

Where $x_{k,q}$the mass fraction of the component k is in the qth phase $S_{jg,k}$ represents the mass transfer source at the phase interface. $\Gamma_{k,q}$is the diffusion coefficient. $W_{gb}, W_{ge}$are the humidity ratio of bulk air and equilibrium air humidity ratio to the liquid desiccant respectively.

Turbulence Model

According to the literature, the regime of the liquid film is mainly wavy laminar flow and that of the moist air has three kinds of possibilities. But even in the turbulent regime, the Reynolds number of the moist air is not rather high in present study. As the flow in the work belongs to the one with relatively low Reynolds number, the standard k–ϵ turbulence model is used to describe the flow process of the liquid film. The turbulence kinetic energy, k, and its rate of dissipation ϵ are obtained from the following transport equations,

$$\frac{\partial \rho k}{\partial t} + \frac{\partial \rho \bar{u}_j k}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\mu \frac{\partial k}{\partial x_j}\right] - \frac{\partial}{\partial x_j}\left[\frac{\rho}{2}\overline{u_j' u_i' u_i'} + \overline{p' u_j'}\right] - \overline{\rho u_i' u_j'}\frac{\partial \bar{u}_i}{\partial x_j} - \mu \frac{\partial \overline{u_i'} \partial \overline{u_i'}}{\partial x_k \partial x_k} \tag{11}$$

$$\frac{\partial(\rho\varepsilon)}{\partial t} + \frac{\partial(\rho u_j \varepsilon)}{\partial x_j} = C_{\varepsilon 1} P_k \frac{\varepsilon}{k} - \rho C_{\varepsilon 2}\frac{\varepsilon^2}{k} + \frac{\partial}{\partial x_j}\left[\frac{\mu_t \partial \varepsilon}{\sigma_\varepsilon \partial x_j}\right] \tag{12}$$

2.3. Initial and Boundary Conditions

Initially, the whole fluid zone is occupied by the air and there is no liquid phase, which means that t = 0, α_g=1, α_l=0 As there is not obvious line between the liquid outlet and gas inlet, the whole bottom is set as pressure outlet boundary. The liquid inlet and gas outlet are set as velocity inlet boundary. It is important to point out that the value of gas outlet velocity is negative to induce the counter current flow of the moist air. In addition, the solution concentration and air humidity can also be set by inputting values at the software interface. The wall is no-slip boundary shear condition and the symmetry is set as symmetric boundary conditions. The gravity effect is not negligible and the surface tension is predominant.

3. SIMULATION

Due to the advances in computational hardware and available numerical methods, CFD is a powerful tool for the prediction of the fluid motion in various situations, thus, enabling a proper design. CFD is a sophisticated way to analyze not only for fluid flow behavior but also the processes of heat and mass transfer. The available computational fluid dynamics software package FLUENT is used to determine the related problems. FLUENT uses a finite volume method and requires from the user to supply the grid system, physical properties and the boundary conditions. When planning to simulate a problem, basic computation model considerations such as boundary conditions, the size of computational domain, grid topology, two dimensions or three-dimension model, are necessary. For example, appropriate choice of the grid type can save the set up time and computational expense. Moreover, a careful consideration for the selection of physical models and determination of the solution procedure will produce more efficient results. Dependent on the problem, the geometry can be created and meshed with a careful consideration on the size of the computational domain, and shape, density and smoothness of cells. Once a grid has been fed into FLUENT, check the grids and executes the solution after setting models, boundary conditions, and material properties. FLUENT provides the function for post processing the results and if necessary refined the grids is available and solve again as the above procedure.

The CFD software FLUENT is used to simulate the two-phase film flow in the 2-D planar vertical channel, as presented in Fig. 1. The governing equations are solved based on a finite control volume technique. As the gravity force is not negligible, the body force weighted pressure discretization scheme is adopted. The Semi-Implicit Method for Pressure Linked Equations (SIMPLE) is used for pressure–velocity coupling. The PRESTO! Pressure interpolation scheme is utilized, which is highly recommended for pressure– velocity coupling. To accelerate the calculation, the first order upwind differencing is selected as the solution of the momentum, energy, turbulence and species transport equations. The geometric reconstruction scheme is used to solve the VOF equation. Transient simulations are conducted with a time step size of 0.001 s. Quasi-steady state is reached for the total transfer rate of heat and mass in the channel with a flow time of approximately 2 s.

According to the literatures, Lithium Chloride (LiCl) has the best dehumidifier efficiency, in comparison to other inorganic desiccants, such as lithium bromide (LiBr) and calcium dioxide

(CaCl2). Hence, LiCl is chosen to be desiccant for dehumidification in the work. The condition of LiCl solution is set as follows: temperature 298 K, mass concentration 30%.Some important physical properties of LiCl solution at the basic point are calculated referring to the literature and listed out in table1. For the moist air, the database of Fluent contains all of its physical properties. The users only need to set the two components air and water vapor and mix them together with the relevant formulation contained by the software.

Table 1. Properties *of LiCl at 298 K and wt 30%*

Density (kg/m^3)	1180
Viscosity (kg/ms)	0.00359
Surface tension (N/m)	0.0893
Specific Heat capacity (J/kg K)	2933

4. GRID INDEPENDENCY CHECK

Table2. *Conditions of the fluids*

Parameters	Air	Desiccant
Temperature (K)	303	298
Inlet velocity (m/s)	0.02	0.07
Mass concentration (%)	2	30

For the grid independency test four different sizes is selected 9e^{-04}m, 6e^{-04}m, 4e^{-04} m and1 e^{-04} m. There is less variations in the volume fraction and temperature of outlet air with respect to grid sizes except 9e^{-04}m. The grid size 6 e^{-04}m has been selected for the simulation;

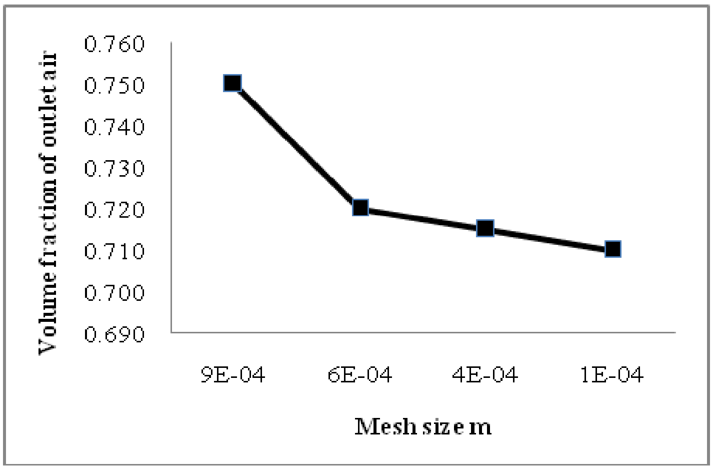

Fig2. *(a) Check for volume fraction*

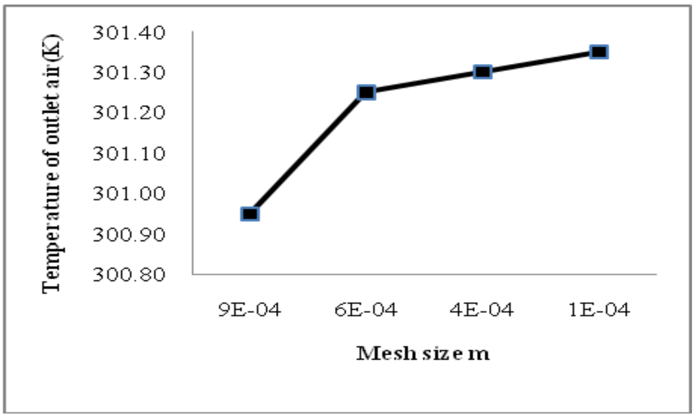

Fig2. *(b) Check for temperature*

5. RESULTS AND DISCUSSIONS

With the above established model, the dehumidification processes of the moist air are simulated in a range of different flow conditions. Table2. Presents the basic conditions of the fluid. The important thermal and physical properties of desiccant at the basic point are listed out in table 1.

5.1. Stages of Film Formation and Volume Fraction in the Dehumidifier

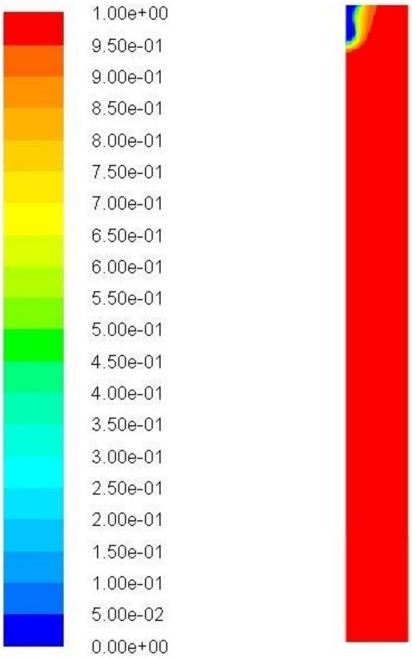

Fig3. *(a) for 0.1 sec*

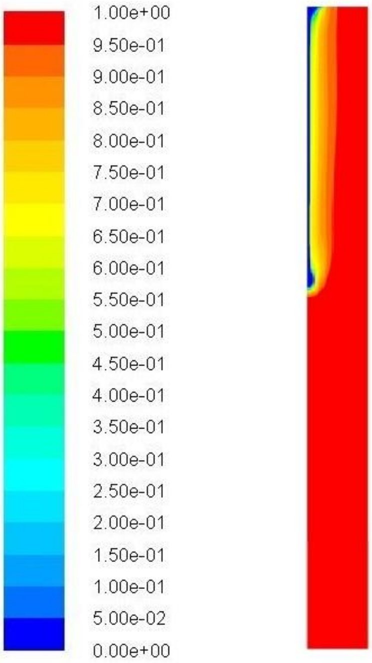

Fig3. *(b) for 0.5 sec*

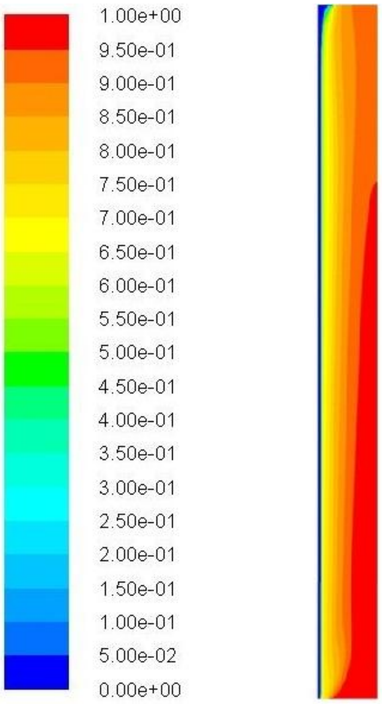

Fig3. *(c) For 1 sec*

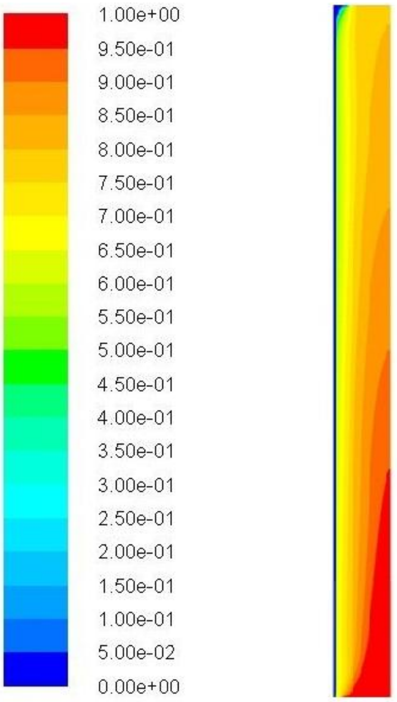

Fig3. *(d) For 2 sec*

The Fig3 shows the stages of film formation and example of dehumidification. The effect of surface tension, gravity and viscous forces causes the desiccant to flow over the plate. As the desiccant velocity is big enough, the liquid solution flows in a continuous film on the plate in the end. Initially the fluid domain is filled with air, the red area represents the air. The formation of film completed at 1 second the simulation extended up to 2 seconds to identify the increase or decrease of the mass transfer.

5.2. Volume Fraction of Humid Air at Different Inlet Air Velocity

In fig 4 (a) to (d) and fig 5, it is clear that the velocity of air affect the dehumidification rate. With the increase of the air velocity, the average mass fraction of water vapor in the outlet air increases as well. The reason is that when the air velocity is bigger the contact time between the air and desiccant is shorter, which decreases the rate of the mass transfer process as per penetration theory. As there are big red areas in the contour diagrams, which manifests no water vapor has been transferred and absorbed by the desiccant. The couture shows that the maximum rate of mass transfer occur at least velocity (0.02m/s).

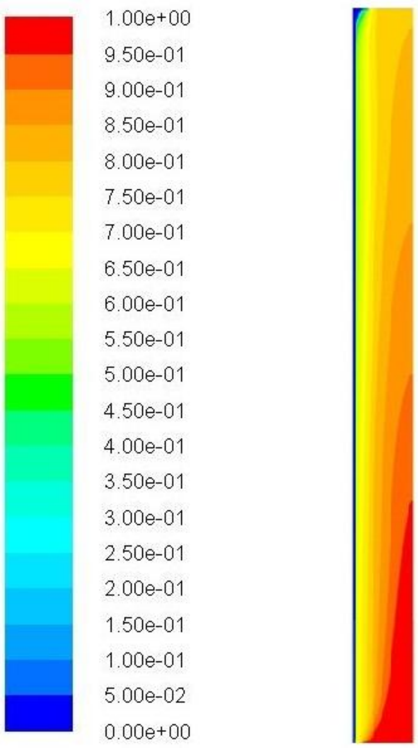

Fig4. *(a) for 0.02 m/s*

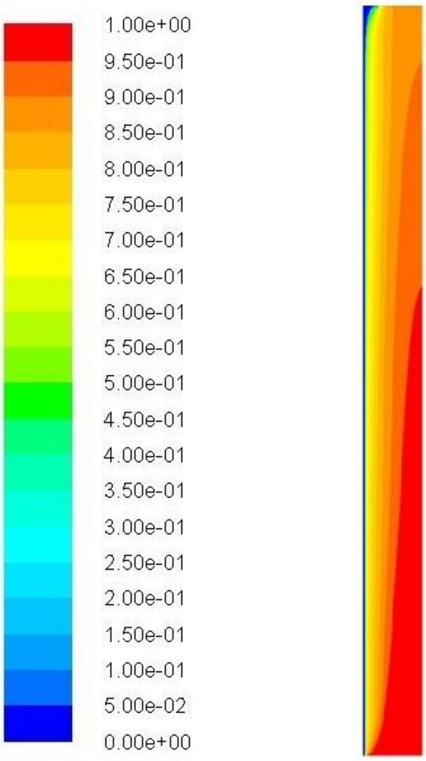

Fig4. *(b) for 0.05 m/s*

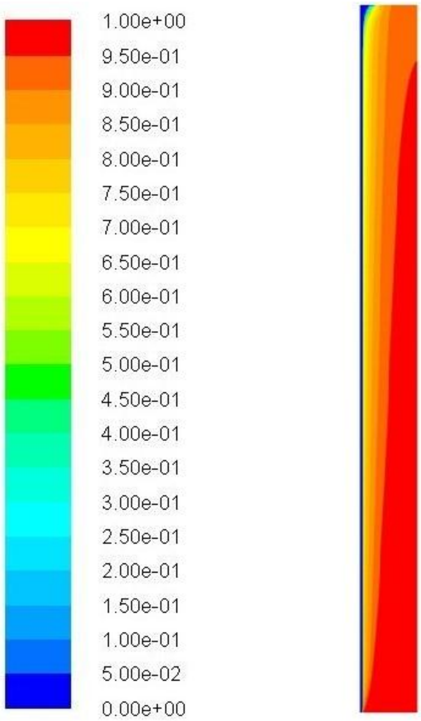

Fig4. *(c) for 0.1 m/s*

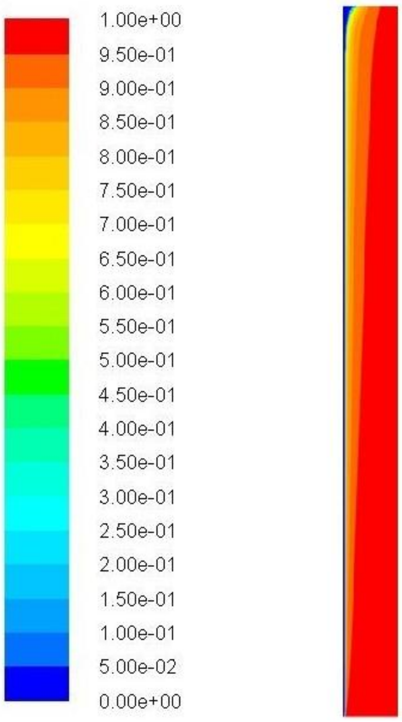

Fig4. *(d) for 0.2 m/s*

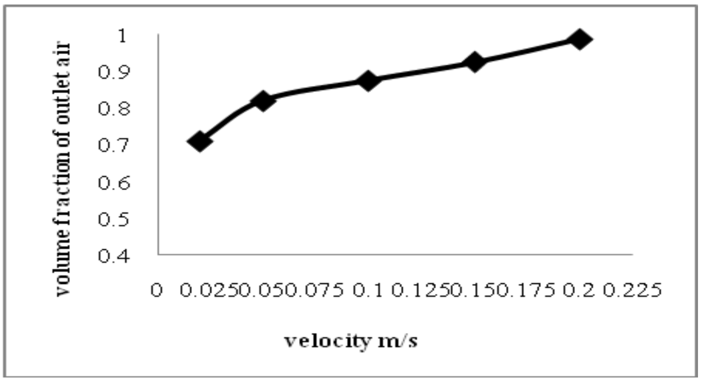

Fig5. *Air velocity v/s volume fraction*

5.3. Temperature of Outlet Air at Different Inlet Velocity

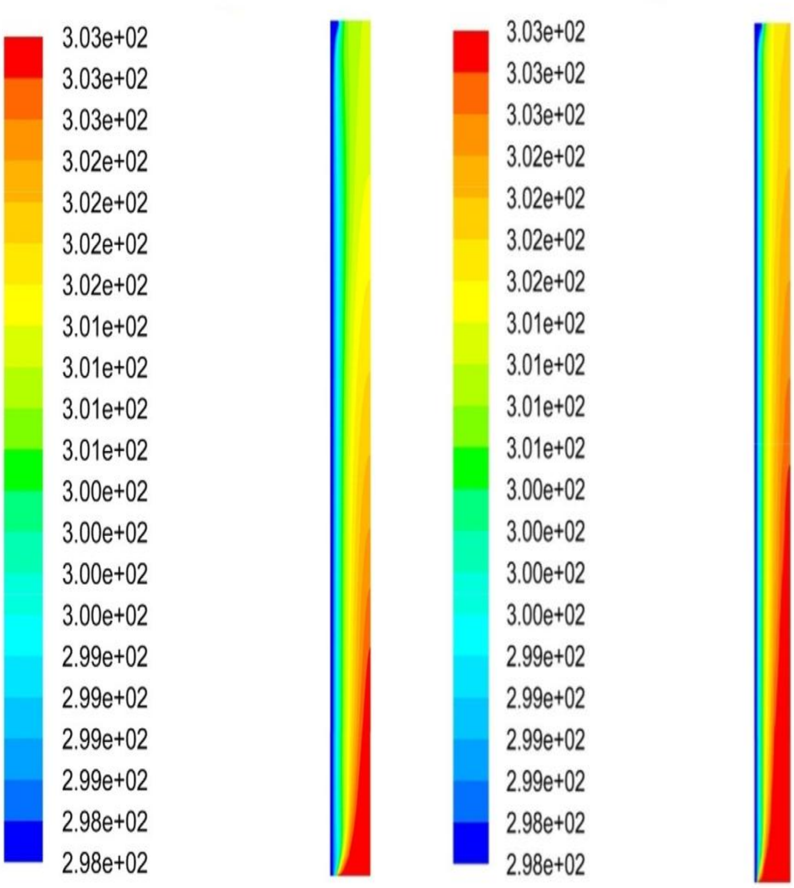

Fig6. *(a) for 0.02 m/s* **Fig6.** *(b) for 0.05 m/s*

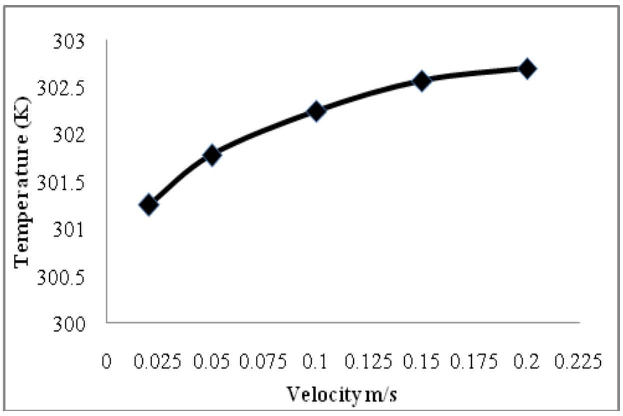

Fig7. *Temperature v/s velocity*

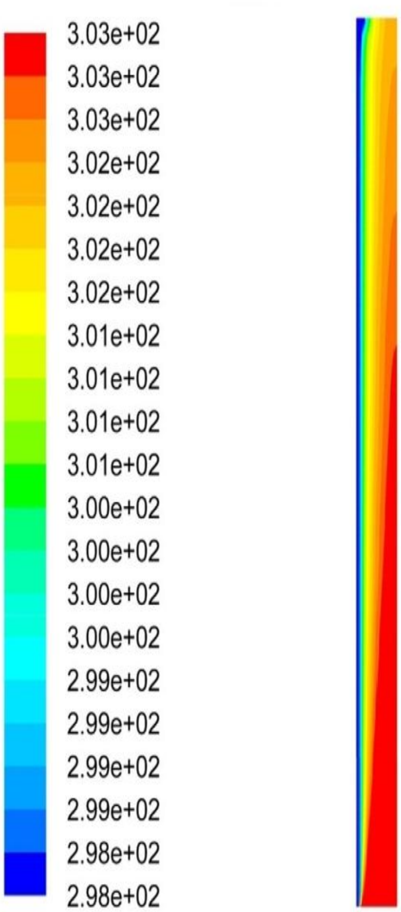

Fig6. *(c) for 0.1 m/s*

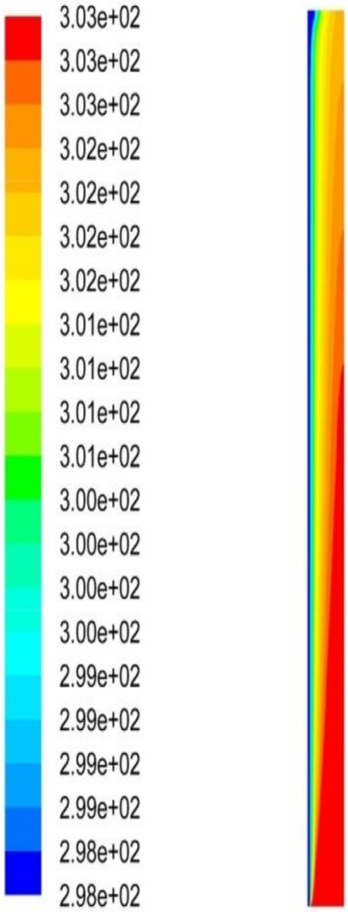

Fig6. *(d) for 0.2 m/s*

Unlike the air velocity-volume fraction relation the outlet air average temperature increases first and then becoming steady a litter with the increase of the inlet air velocity. In fig 7, it shows the relation as stated and fig 6 (a) to (d) shows the contours of temperature at different air velocities. There are two factors which have effects on the air temperature. On one hand, as the desiccant temperature is lower than that of the air, the air temperature will reduce by sensible heat exchanging with the desiccant. On the other hand, the water condensation of the air produces some latent heat, which will increase the air temperature. The above two factors are coupled, resulting in the outlet air temperature variation tendency.

6. CONCLUSION

This model is simulated the heat and mass transfer process of two dimensional dehumidifier. The model is justified to be able to predict the performance of the dehumidifier. The model has few advantages over the existing models which we have already discussed in the literature.

- The changed velocity field is calculated by considering the effects of gravity, viscosity and surface tension, all of which were generally ignored in previous models.
- The penetration mass transfer theory is used to replace the two film theories, so that it becomes possible to observe the dynamic heat and mass transfer process of the dehumidifier.

The parametric studies are conducted based on this model in a range of different flow conditions. Through the simulation, it is found that the air velocity plays a critical role on the performance of the dehumidifier, and it has to be matched with the channel geometric size for optimization. The mass transfer rate has described in terms of volume fraction and the velocity 0.02 m/s has given the maximum mass transfer rate. The temperature of outlet air not reaching the liquid temperature because of the effect of sensible heat or the latent heat of condensation.

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