COMPUTATIONAL FLUID DYNAMICS (CFD) PREDICTION OF FLOW AND TEMPERATURE DISTRIBUTION IN DRYING COMPARTMENT

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This report is submitted as partial requirement for the fulfillment of the Bachelor of Mechanical Engineering (Thermal Fluids) Degree Programme

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DECLARATION

"I hereby, declare this report is the result of my own research except as cited in the references"

Signature : …….

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Specially dedicated to my family, friends and companion

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ABSTRAK

Laporan ini berkaitan dengan simulasi dan analisis Dinamik Bendalir Komputeran (CFD) kepada pengeringan baju dengan haba buangan dalam kabinet pengering CDURH (*clothes drying using rejected heat*). Keberkesanan kabinet pengering dikaji dengan menjalankan analisis terhadap aliran udara panas dan suhu di dalam kabinet tersebut. Daripada kajian literatur, didapati kebanyakan simulasi CFD yang melibatkan kain atau tekstil menggunakan model kain yang diterbit kepada program CFD dengan menyusun semula persamaan konservasi jisim, tenaga dan momentumnya. Dengan cara yang sama, penulis telah mengaturcarakan persamaan yang mewakili pengeringan kain kepada CFD program dengan menggunakan *user defined function.* Pengesahan keputusan simulasi telah dijalankan dan didapati model pengeringan kain yang diterbit dapat meramalkan jumlah masa yang diperlu untuk pengeringan kain basah kepada keadaan yang seimbang degan sekitar dengan ralat 1.3 % dan 2.4 % pada keadaan tertentu. Model yang sama digunakan untuk pengering baju yang sebenar dan simulasi CFD dijalankan. Keputusan simulasi yang didapti dikaji dan dianalisis untuk menentukan parameter-parameter yang penting dalam rekabentuk pengering baju.

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ABSTRACT

The report deals with the computational fluid dynamic (CFD) simulation and analysis of the clothes drying using rejected heat (CDURH) drying compartment. The performance of the drying cabinet is analyzed by observing on the hot air flow and temperature distribution inside the cabinet. From the literature studies, most of the fabric or textile CFD simulations applied the fabric model that had been input to the CFD program by recasting the corresponding governing transport equations. Thus, similar approach is used in this project where the wet fabric drying model is developed by recast the governing equations of the porous medium into the Fluent solver using the user defined function. Validation is performed to the simulation result and fabric model developed is found able to predict the total drying time required for the fabric to be dried to equilibrium condition with percentage errors of 1.3 % and 2.4 % for given conditions. The same model is applied to the actual clothes dryer and CFD simulation is performed. The simulation result is then studied and analyzed to determine the important parameters in designing the clothes dryer.

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LIST OF SYMBOLS

RAC = Residential air conditioner

CHURH = Clothes drying using rejected heat

CFD = Computational Fluid Dynamic

ρ = Density, kg/m^3

t = Time, s

$\vec{v}$ = Overall velocity vector, m/s

S_m = Mass flux, kg/m^2.s

p = Pressure, Pa

$\bar{\bar{\tau}}$ = Stress tensor, Pa

g = Gravitational acceleration, m/s^2

$\vec{F}$ = Force vector, N

E = Total energy, J

v = Velocity magnitude, m/s

h = Species enthalpy, J/kg

k_{eff} = Effective thermal conductivity, W/mK

c_p = Heat capacity at constant pressure, J/kg-K

$\vec{J}$ = Mass flux; diffusion flux, kg/m^2.s

S_h = heat source, W/m^2

Y = Mass fraction

S_i = Source term for porous medium, N

α = Permeability, m^2

μ = Viscocity, kg/ms

C_2 = Resistance factor

D_p = Mean particle diameter, m

ϵ = Void fraction of porous media

Nu = Nusselt number

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h_{sf} = Convection heat transfer coefficient, $W/m^2.K$

d = Diameter of spherical particles, m

k_f = Effective thermal conductivity, W/m.K

Re = Reynolds number

Pr = Prandtl number

$\dot{Q}_{conv}$ = Total heat transfer in convection, W

A = Specific surface area of fabric, m^2

T_s = Surface temperature, K

T_∞ = Air stream temperature, K

Sh =Sherwood number

h_m = Mass transfer coefficient, m/s

D = Mass diffusivity of water vapor, m^2/s

Sc = Schmidt number

Le = Lewis number

α_v = Thermal diffusivity, m^2/s

$\dot{m}_{conv}$ = Total mass transfer in convection, kg/s

$\rho_{v,s}$ = Mass concentration of water vapor in fabric surface, kg/m^3

$\rho_{v,\infty}$ = Mass concentration of water vapor in air stream, kg/m^3

$P_{v,}$ = Vapor pressure of water, Pa

R_v = Gas constant of water, (0.4615 kJ/kg.K)

Ø = Relative humidity of air, %

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CHAPTER I

INTRODUCTION

1.1 Background

Conventional clothes dryer or a tumble dryer is used to remove the moisture of the clothes or fabrics that have been washed. The domestic dryer consists of a drum which the heated air is circulated through to evaporate the moisture of the loaded clothes. Generally, most the household tumble dryers are powered electrically or gas.

Due to the increases of the awareness about energy saving, most household electrical appliances have been improved to achieve power saving purpose. Clothes drying using rejected heat of residential air conditioner (RAC), also called the CDURH unit were studied by Deng and Han (2003). Based on their design, the waste heat from condenser is directed through the air duct to a drying cabinet for clothes drying process. The design of the CDURH drying compartment and the hanging rack are shown in Figure 1.1 and Figure 1.2 respectively. The dimension of the drying cabinet is 920 mm long, 550 mm wide and 550 mm height and the smaller size drying rack, with 760 mm long, 450 mm wide and 460 mm height is placed inside the drying compartment. The CDURH unit could gradually reduce the energy use since there is only 1.2% of the electricity used by the tumble dryer is needed to complete the same clothes drying job using the CDURH drying compartment.

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This project continues the CDURH research by analyzes and investigates the air flow pattern and the temperature distribution of the drying compartment with the aid of a computational fluid dynamic (CFD) program. Simulations with various configurations of inlet air velocity, compartment size, textile material are observed.

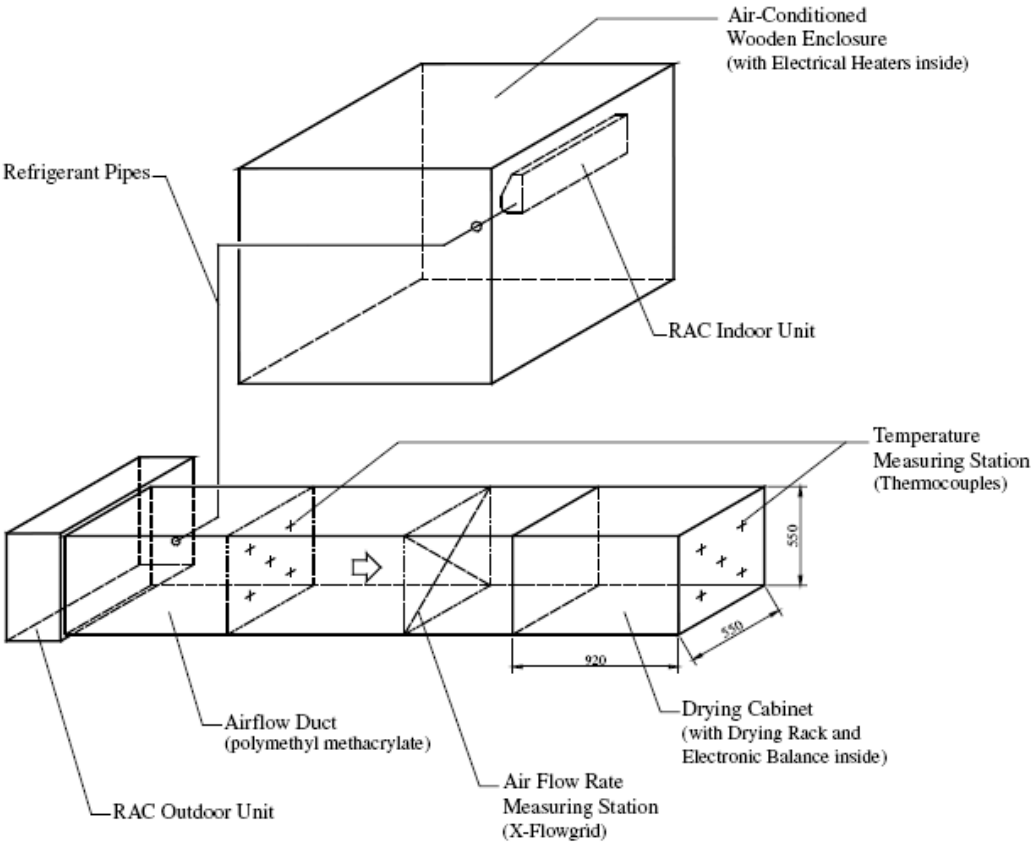

Figure 1.1: Schematics of the CDURH drying compartment
(Source: Deng and Han, (2003))

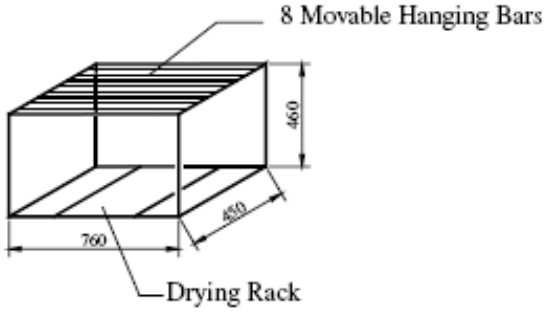

Figure 1.2: Drying rack inside the drying compartment
(Source: Deng and Han, (2003))

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1.2 Objectives

- To develop the wet fabric drying model for the CFD solver
- To validate the simulation result of clothes drying process
- To study and analyze the hot air flow and temperature distribution of drying compartment
- Predict the air flow and temperature distribution of the clothes dryer by running simulation with different parameters

1.3 Scopes

The project will focus on the analysis of the drying cabinet. The scope covered:

a) Literature study on clothes drying
b) Drawing of the drying compartment
c) Simulation of clothes dryer using Fluent to obtain the air flow pattern and temperature distribution

1.4 Problem Statement

The CDURH drying compartment uses the waste heat from air conditioner to dry the washed clothes. However, this new type of clothes dryer is still under development and not available in the market yet. The major concern of design the drying cabinet is that the limited energy available from the condenser of air-conditioner. Thus, an efficient drying cabinet must be designed so that its drying performance is in satisfaction. Since the drying of fabrics is a type of the fluid flow problem, the best solution in developing the drying cabinet is to visualize the drying mechanism of wet clothes and study the effects of air flow velocity, temperature and relative humidity to the drying performance of the CDURH unit.

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CHAPTER II

LITERATURE REVIEW

2.1 Background

The clothes drying using rejected heat (CDURH) drying compartment consists of an air flow duct, a drying cabinet and a drying rack. By connecting the residential air-conditioner outdoor unit (condenser) with the air flow duct, the heated air flow through the wet clothes in the drying compartment to evaporate the moisture content in the clothes. There are several studies on the tumbler clothes dryer had been done by researcher, which focus on determining the parameter of energy consumption and improving the performance of the clothes dryer.

Yadav and Moon (2008) have done an analysis on the clothes drying process inside the household electric tumbler clothes dryer to investigate the various thermo-physical parameters that affecting the energy consumption. They developed the simulation model by breaking the complete drying process into four successive stages, which are the drying models across the blower, the drum's external surface, air heater and the drum respectively. Experiment was also conducted on test setup based on tumble dryer to find out the parameter value. Comparison of the simulation and experimental results was done to validate the simulation model. From the study, it was found that the important parameters in determining the performance of the tumbler dryer include the inlet relative-humidity, mass per unit area of the cloth, bone-dry mass of cloth and water content lost.

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Ng and Deng (2008) did a research on developing a new termination control method for a clothes dryer by using both mathematical modeling and experimental approaches. They have developed the drying models in a constant-rate drying period (CRDP) and a falling-rate drying period (FRDP) based on existing knowledge and theories of drying. An experiment on cotton fabrics drying in different drying environments was carried out to determine the unknowns, critical point and the drying index in the drying models. Meanwhile, the experimental results also showed that the models were adequate and can be used in new termination control design.

2.2 Development of Numerical Fabric Model

In the development of the fabric model, most of the studies developed the textile model by modifying and applying the theory of heat and mass transport through the porous material. There are several studies focused on determining the thermal comfort of clothing by inspecting on the interaction between the moisture transport and heat transfer in the fabric.

Hussain and Dincer (2003) has presented an article deal with the numerical modeling of heat and moisture transfer during the drying process of a two-dimensional rectangular object subjected to convective boundary conditions. Assumptions were made where the drying takes place as a simultaneous heat and moisture transfer whereby moisture is vaporized by air, which passes over a moist object. By discretizing the governing equations representing the drying process in a 2-D rectangular object using and explicit finite-difference approach, then he developed the computer code to predict the temperature and moisture distributions inside the object. The results of numerical simulation were then validated by experimental data. From the research, the transient temperature and moisture distribution inside the rectangular object at different time periods were obtained.

According to Gibson (1996), the comprehensive theory for mass and energy transport through porous media presented by Whitaker (1977) could be modified so that it is applicable to fibrous materials. He developed a set of partial differential equations describing time-dependent transport properties of hygroscopic and non-

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hygroscopic clothing materials by including many important factors which are usually ignored in the analysis of heat and mass transfer through textile materials. The equations also allows for the unsteady capillary wicking of sweat through fabric structure, condensation and evaporation of sweat within various layers of the clothing system, forced gas phase convection through the porous structure of a textile layer and the swelling and shrinkage of fibers.

The partial differential equations developed by Gibson were then used in the modeling of convection/ diffusion process in porous textiles with inclusion of humidity-dependent air permeability, which was done by Gibson and Charmchi (1997). By neglecting the gas phase convection and liquid capillary transport, the accurate models for heat and mass transfer through porous textile based materials were developed. They developed the numerical code to solve the set of nonlinear coupled equation and applied to an experimental apparatus designed to simulate transient and steady state convection/ diffusion conditions of textile materials. From their research, it was found that the temperature changes of hygroscopic textiles subjected to step changes in environmental relative humidity are due to sorption of water vapor from the flows on the two sides of the material, and it relates to textile fiber equilibrium sorption isotherms (contour line of equal temperature) and sorption kinetics, as well as the physical structure and thermal properties of the textile. In the conditions when both combined diffusion and convection occur, the effect of fiber swelling results in significant changes in the resistance to convective flow and the total mass flux across the textile layer.

There was a study done by Ghali et al. (1995) on modeling heat and mass transfer in fabric. They constructed a numerical model simulating the heat and mass transfer in fabric during the wicking process (capillary action) applied to cotton and polypropylene materials. Simulation of the model shows that there is a significant temperature gradient formed between the fabric and water regions. Also, they found out that the variation of the fractional saturation is continuous along the specimen. Experiment was conducted to obtain the transient temperature distribution during wicking process for the fabrics and the numerical model was validated. They concluded that energy is transported in four different forms in the wicking process which is by conduction, diffusion of moisture in the plane of the fabric, convection

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of liquid in the plane of the fabric and evaporation of moisture to the atmosphere surrounding the fabric.

Heat exchange between human body and the environment is significantly affected by the dynamic response of the clothing system. Ghali et al. (2002) conducted a study on the modeling of heat and moisture transport by periodic ventilation of thin cotton fibrous media to investigate the coupled convection heat and moisture transfer within the clothing system subjected to sinusoidal air layer thickness variation. They also developed a mathematical model to predict the periodic fabric regain, the fabric temperature and the transient conditions of the air layer located between the fabric and the skin. Several experiments were conducted in environment chambers under controlled conditions using a sweating hot plate at 35^{o}C which represents the human skin and a gear motor to generate the oscillating fabric motion. The experiment was first done using a dry isothermal hot plate to measure the sensible heat transfer. Then, the second set of experiments was conducted with an isothermal sweating hot plate to obtain the total heat (sensible and latent) transport from the plate. They found out that the regain increases sharply in the initial period of exposure and then increases at a slower mean rate in an oscillating pattern. As the thickness of the air layer increases, the air flows from the outside and the fabric regain decreases due to the lower humidity of the outside air. When the thickness of the air layer decreases, fabric regain tends to increase since the higher humidity air flows out from the inside air layer. The predicted heat and mass transport through the air spacing layer and fiber clothing system from the mathematical model shows good agreement with the experiment measured time-averaged values with the discrepancy between measured and calculated heat losses below 32%.

Ghali et al. (2006) have done a research on the heat-moisture interactions and phase change in fibrous material. The research focused on the phase change phenomena associated with the adsorption of moisture into fibers, and the release or absorption of heat associated with the change of phase. They developed the mathematical relationships that describe the heat and moisture interaction in clothing system. From the model of coupled heat and moisture transport, they found out that the increase in moisture regain results in the increase in temperature. The small changes in regain can result in large temperature changes due to the heat of sorption

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is large. On the other way, the heat flow are driven by the temperature gradients, thus the adsorption and desorption of moisture by the fibrous media has large influence on the heat flux through the media as well. For porous media drying, they also concluded that the small decrease in regain results in large cooling effect, which could eliminate the partial pressure gradient that is driving the moisture removal. Thus, the drying process proceeds at very low rate in the absence of a heat source.

Li and Zhu (2003) studied on the simultaneous heat and moisture transfer with moisture sorption, condensation and capillary liquid diffusion in porous textiles. They have developed a dynamic model of liquid water transfer coupled with moisture sorption, condensation, and heat transfer in porous textile by incorporating the physical mechanism of liquid diffusion in porous textiles into a coupled heat and moisture transfer model developed previously. An equation describing the liquid diffusion behavior is also developed in the form of diffusion coefficient. Then, they developed the numerical computational scheme to solve the coupled equations involves a fractional volume of fluid method. In order to validate the model, the experiments measuring fabric surface temperature are conducted. From the computational result, they found that the dry fabric exhibits three stages of transport behavior responding to change in humidity. At the first stage, the water vapor diffusion and liquid water diffusion are the dominating process and reach to steady states within a second. Mean while, the liquid flow out of the regions of higher liquid content to drier regions, driven by surface tension force. Followed by second stage, a very slow process; the moisture sorption of fibers which take a minute to few hours to complete. And finally the third state is the steady state where all four forms of moisture transport and the heat transfer process become steady and the coupling effects among them become less significant.

Fohr et al (2002) has developed a model of heat and water transfer through layered fabrics in wearing clothing. All particular properties of recently developed fabrics such as hydrophobic or hydrophilic treatment, membranes glued onto a layer and surface modification of the textile (abrading) were taken into model consideration. By one dimensional transfer in a porous medium, the partial differential equations of energy and mass balance were solved to observe the physical phenomenon of fabric such as sorption or desorption; free water

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condensation or evaporation; liquid, vapor and absorbed water diffusion and heat conduction and contact resistances between layers. Then the results were validated by comparing with the existing in literatures. They concluded that the hygroscopic character of a fabric can be expressed by a diffusion coefficient, which is a function of water content.

A research was conducted (Crow and Osczevski 1994) to examine how fiber and fabric properties affect the drying time of a wide range of textile materials. They conducted an experiment by measuring the time taken for the freely absorbed water in each specimen to be completely dried in the atmosphere of 20 ^{o}C and 65% relative humidity. The time to dry was taken when the mass of the specimen reached 105% of its dry mass with the extra 5% reflects the accuracy of the balance used. They found that the drying time of a fabric is independent of its fibre type or regain, but dependent on the amount of the water initially contained in the fabric which depends to a great extent on the thickness of fabric. The water evaporation rate in fabric was also found to be greater than equivalent volume of free standing water.

2.3 Drying Model Development and Simulation

The drying process of the object is depending on the environmental factors such as the air velocity, ambient temperature and pressure. The drying study is applicable to variety of materials such as textile, wood, and food. There are plenty of studies have been done on the food drying process. Many drying models were developed and simulated so that the dried food quality could be predicted and controlled well.

Dietl et al. (1997) did a research on the efficient simulation of the heat and mass transfer processes during drying of capillary porous/ hygroscopic materials. They introduced the numerical model that describing the hygroscopic materials and simulated the convective heat and mass transfer to determine the coefficients for the moisture conductivity and vapor diffusion resistance. The single solid model developed is based on the conservation of heat and enthalpy flow rates as well as

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