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# Drying performance and thermal transient study with solar radiation supplemented by forced-ventilation

M.O. Abdullah *, F.A. Mikie, C.Y. Lam

*Department of Mechanical Engineering & Manufacturing, Faculty of Engineering, Universiti Malaysia Sarawak, 94300 Kota Samarahan, Sarawak, Malaysia*

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**Abstract**

A solar attire or cloth dryer has been designed, constructed and experimentally tested. The result shows that solar dryer supplemented with forced-ventilation has higher drying rate of 0.43 $\mathrm{kg\,h^{-1}}$ and shorter completion drying time of 3 hours compared to solar dryer with natural ventilation which has a drying rate of 0.25 $\mathrm{kg\,h^{-1}}$ and drying time of more than 4 hours for a typical day. Consistent with the experiments, the preliminary computational results based on the Navier–Stokes thermal transient simulation technique able to demonstrate the temperature rise prevailing in the solar cum forced-ventilation system associated with the internal heat flux due to solar radiation and moisture removal. Good agreement is found between the numerical simulation and the corresponding experimental measurements. Parametric study by simulation was conducted subsequently to investigate the feasibility of employing higher capacity fans, i.e. higher forced-ventilation rates, on energy stored if the current system operated under same ambient weather conditions. Initial comparison studies based from both experiment works (natural ventilation vs. forced-ventilation) and simulation (temperature rise vs. forced-ventilation rates) have shown that the application of higher ventilation rates would possibly further improve the dryer's performance and cause an increase of local heat flux and temperature rise, especially in the early stage of drying.


*Keywords:* Solar energy; Heat flow and ventilation; Computational fluid dynamics; Navier–Stokes; Attire drying; Heat flux

## 1. Introduction

The use of solar energy for drying purposes must have been done by our ancestors in any part of the world throughout the years. As solar energy is available around the globe and that it is cheap, this form of energy had been and can be continuously utilized for our drying requirements as well as other daily activities. Ekechukwu and Norton [1] had classified the solar drying systems primarily according to their heating modes and how the solar heat is utilized, i.e. passive (natural-circulation) or active or forced-convection (hybrid solar dryer).

The experimental study of drying had been investigated by many researchers. Most of the solar dryers investigated and reported in the literature are for agricultural products notably fruit, vegetable or crop drying, for e.g. Sutherland [2], Kilkis [3] and Condorí et al. [4].

While a great deal of research had been reported on the agricultural drying. A limited number of studies have been reported on attire/cloth or textile drying. Furthermore, the attire drying techniques were utilizing either in the form of steam by burner or waste heat from heat pump/air conditioning units. The present study described the use of solar energy for both drying and ventilation to enhance the drying process of attire. There is a global-wide need for low energy consumption equipment to dry clothes in areas of high humidity and low wind speed. The use of conventional simple cloth line of course is the cheapest means but it needs longer period in order to dry most clothing.

Van Denventer [5] described a method of utilizing superheated steam for cloth drying with direct contact. Adnot [6] discussed the adaptability of metal fiber burners to industrial paper and textile drying techniques. This method of drying of textiles involving evaporation and combustion require a careful control, high temperature chamber, typically around 600 °C [7].

* Corresponding author. Tel.: +60 82 679 301 (direct line); fax: +60 82 672 317.

*E-mail address:* amomar@feng.unimas.my (M.O. Abdullah).

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**Nomenclature**

| | | |
|---|---|---|
| $A$ | the surface area of the dryer | $m^2$ |
| $ACM$ | air change per minute (air change $m^{-1}$) | |
| $C_p$ | specific heat capacity | $J\,kg^{-1}\,K^{-1}$ |
| $k$ | thermal conductivity | $W\,m^{-1}\,K^{-1}$ |
| $t$ | time | s |
| $\Delta T$ | temperature difference between inside and outside of dryer | °C |
| $i$ | $i$-direction | |
| $j$ | $j$-direction | |
| $k$ | $k$-direction | |
| $N_a$ | the number of air changes per minute within the dryer (Eq. (2)) | |
| $N$ | the number of radiant surface | |
| $Q_s$ | total direct solar gain in watts | W |
| $Q_v$ | total ventilation gain in watts | W |
| $Q_k$ | net heat-flux arriving at the surface $k$ (Eq. (7)) | |
| $u_i$ | velocity | $m\,s^{-1}$ |
| $Sgf$ | the solar gain factor | |
| $G$ | the total solar radiation on the dryer | $W\,m^{-2}$ |
| $x_i$ | length | m |
| $V$ | the total internal volume of the dryer | $m^3$ |
| $p$ | pressure | $N\,m^{-2}$ |

*Greek symbols*

| | | |
|---|---|---|
| $\psi$ | exchange coefficient (Eq. (3)) | |
| $\tau_{ij}$ | stress tensor (Eq. (5)) | |
| $\varphi$ | dependent variable (Eq. (3)) | |
| $S^{\varphi}$ | source/sink term (Eq. (3)) | |
| $\rho$ | density (Eq. (3)) | kg |

Klöcker et al. [8] reported a laboratory prototype laundry dryer equipped with $CO_2$ heat pump modified from a commercial hot air laundry dryer. Ameen and Bari [9] described the utilization of the air conditioner waste heat for drying clothes. They found that the waste heat drying method took about 2 hours compared to 2.5 hours for a commercial dryer. While recovery technique using waste heat from heat pump or the condenser of air conditioning unit was feasible but the running cost of an air conditioner or heat pump itself was normally considered as expensive.

Apart from experimental study, some of the theoretical treatment of the subject can be cited. The progress of the zones of heat and mass transfer during the aeration of the grain beds has been described and estimated by the method of characteristics by Ingram [10]. Drying curves obtained from the data-fitting to a number of mathematical models to investigate the effects of drying air temperature, velocity and relative humidity on the drying of apricot were evaluated by the multiple regression method by Togrul and Pehlivan [11]. Torres-Reyes et al. [12] described semi-empirical models for the thermal characterization of an experimental the result of which is an indirect modeling method, derived from the Second Law of Thermodynamics.

For the attire/cloth drying application, Adnot [6] presented a mathematical model on the thermal behavior of an adapted metal fiber burner in a cubic chamber. Gopalnarayan et al. [13] described a simulation method for a closed loop pump assisted dryer for clothes drying.

In the present study, an affordable solar attire dryer had been designed, built and tested. To the best knowledge of the authors, this use of solar energy for drying coupled with forced-ventilation by solar-powered fan, to enhance the drying process of attire is novel. For the experimental part, for comparison purpose, two tests on the dryer had been carried out by the authors, viz. with both natural ventilation and forced-ventilation. For the computational investigation, a finite volume method based on the radiation–ventilation characteristics is used to investigate the transient temperature build up behavior in the forced-ventilation dryer. The subsequent parametric study is conducted to further investigate the feasibility of employing higher capacity ventilation fan, i.e. to investigate the effect of forced-ventilation rates on the initial temperature rise and local heat flux generation. The experimental tests were conducted at Kota Samarahan, Kuching, East of Malaysia (Lat:01°29′; long.: 110°20′E) and thus the computer simulation is also done based on local tropical condition with high humidity of around 85% and low wind speed, however the findings can be useful at many locations.

## 2. Design description and air flow mechanism of the solar attire dryer

The solar attire dryer developed in this study by the authors, Lam [14], is made from aluminum rod, transparent acrylic plastic sheet, PVC pipe, solar-powered panel with charge controller and ventilation fans. Fig. 1(a) and (b) are the schematic diagrams showing the front view and side view of the solar attire together with the components and the dimensions. The total capacity of the dryer is about 15 clothes. All the surfaces of the enclosure are transparent to maximize the quantity of sunlight absorption, to provide enough heat retention via the "greenhouse effect" also to permit the visual inspection of the clothes. Aluminium beam is chosen as the frame of attire dryer because of it's rigidity while having light weight properties. The most common glazing material used for drying is glass but glass blocks are known to break easily beside heavy in weight for the current usage. Acrylic plastic is half the weight of glass, impact resistant, unaffected by sun or salt spray and has a temperature range up to 70 °C for continuous service [15]. The present study therefore opted for acrylic plastic for the construction. The specifications and properties of the acrylic, solar PV panel and the ventilation fans used are given in Tables 1, 2 and 3, respectively. Synthetic plastic hanger frames are used for hanging the clothes.

Fig. 2 shows the processes involved, i.e. solar radiation, airflow and ventilation in the solar attire dryer. Solar radiation

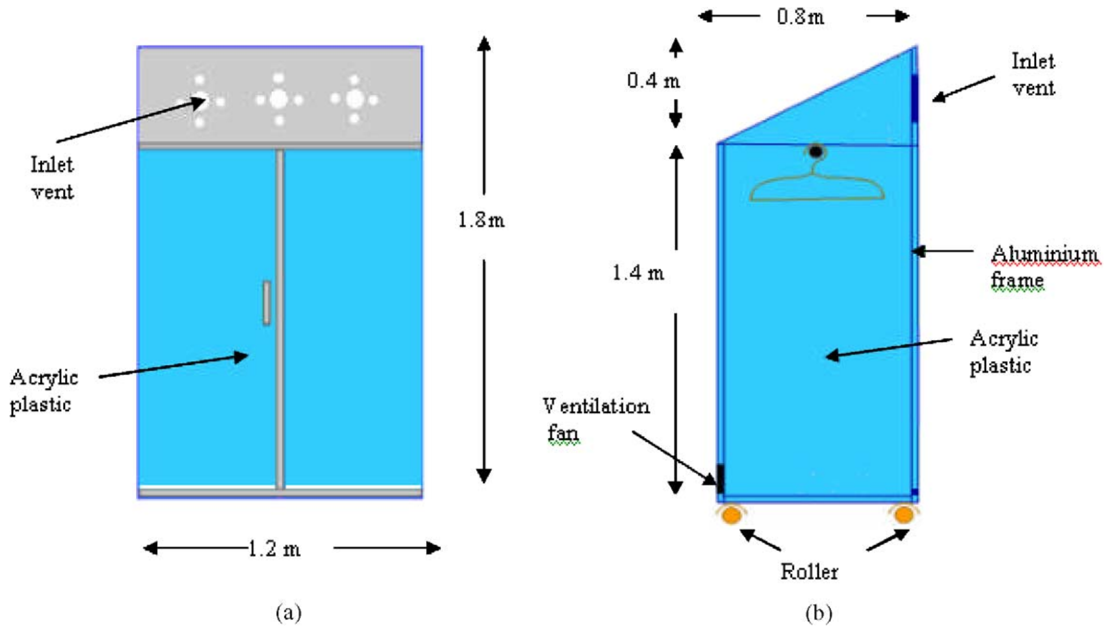



Fig. 1. Front (a) and side (b) views of the solar attire dryer (roller not shown).

Table 1
Acrylic properties

| Physical properties | |
|---|---|
| Water absorption | 0.3–2% |
| Moisture absorption at equilibrium | 0.3–0.33% |
| Electrical resistivity | $1 \times 10^{14}$–$1 \times 10^{15}$ ohm-cm |
| Heat capacity | $1.46 \times 10^3$ J kg$^{-1}$ K |
| Thermal conductivity | 0.19–0.24 W m$^{-1}$ K |
| Refractive index | 1.49–1.498 |
| Transmission, visible | 80–93% |

Table 2
Specification of the Solar PV Panel. Model: GL130/M65

| | |
|---|---|
| Power (±10%) | 42.0 W |
| Current | 2.9 A |
| Voltage | 14.5 V |
| Short circuit current | 3.26 A |
| Open circuit voltage | 18.0 V |

Table 3
Ventilation fan specifications. Model: Sanyo Denkki 109E1212H14

| | |
|---|---|
| Current | 0.15 A |
| Voltage | 12 V (DC) |
| Flow-rate | 0.005 m$^3$ s$^{-1}$ |

through the transparent sheet caused temperature rise internally due to green house effect. Ventilation process either in the form of natural ventilation or forced-ventilation helps in removal of the humid dense air through the holes and fan located at the bottom of the structure. Drying occurred when relatively low-humidity air passed over the wet cloth surface picking up moisture which is then carried away through ventilation. The buildup of internal heat flux helps in the separation of the moisture from the cloth surface through enhancement processes of evaporation, convection and diffusion.

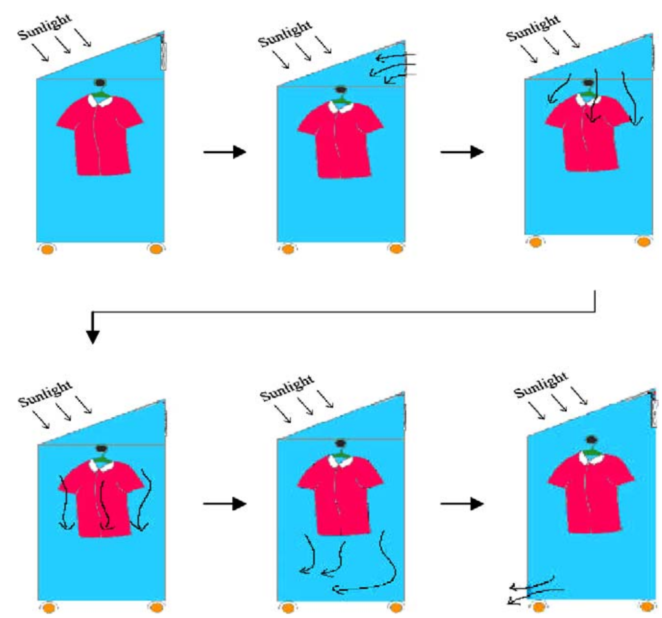



Fig. 2. The flow pattern of air inside the dryer [14].

## 3. Design consideration, experiment work and results

### 3.1. Basic design consideration

Direct solar gain and ventilation gain are two important parameters for design consideration of the enclosure of the attire dryer. Direct solar gain through transparent elements is estimated by the following equation [16,17]:

$$Q_s = G \times A \times Sgf \tag{1}$$

The solar gain factor, $Sgf$ is a function of the type of material and represents the amount of direct radiation that actually makes it through the element and into the dryer.

Ventilation gains was estimated according to Stoecker and Jones [16]:

$$Q_v = 20 \times N_a \times V \times \Delta T \tag{2}$$

The value 20 in Eq. (2) resulted from the fact that moist air is assumed to has a volumetric heat capacity of $1200\ \mathrm{J\,m^{-3}\,K}$ and that the flow rate is given as a factor of air changes per minute. Since 1 W equal $1\ \mathrm{J\,s^{-1}}$, then $(1200\ \mathrm{J\,m^{-3}\,K})/(60\ \mathrm{min}) = 20\ \mathrm{J\,m^{-3}\,K\,min}$.

### 3.2. Experimental work

The primary aim of the experiment work is to investigate the attire drying ability under forced-ventilation condition (case I) while natural ventilation condition (case II) also tested merely for comparison purpose. The internal dryer temperature, ambient temperature and room temperature were recorded every 30 minutes using a digital type K thermometer, model ACEZ 328 (accuracy: ±0.3%). Weight of the clothes with hangers was recorded using a laboratory balance (accuracy: ±0.1%) fixed on the common rod attached with the hangers inside the dryer. Relative humidity was recorded with the EXTECH Instrument® humidity meter, model EXTECH 4465 (accuracy: ±0.1% RH).

*Ambient weather conditions*: The data reported here was recently obtained experimentally by the authors [18], which were taken at two typical sunshine days during the testing period carried out between 20 January 2005 and 25 February 2005. The tests were conducted on sunny days, i.e. no rain, with close or almost similar outdoor weather conditions, i.e. ambient relative humidity around 80–85% and wind speed in the range of $0.45\ \mathrm{m\,s^{-1}}$–$0.89\ \mathrm{m\,s^{-1}}$. The test days selected were on the 27 January 2005 (case I) and on the 8 February 2005 (case II) respectively. Test location was at outdoor, approximately 2 m from the Mechanical workshop building of Universiti Malaysia Sarawak, Kuching (Lat:01°20′E, height above mean sea level: 21.73 m).

*Attire samples description*: Type: T-shirt, thickness range: 1.0 mm–1.5 mm, cloth materials: 100% nylon, color: brown. No. of clothes used for testing: 10 per batch.

### 3.3. Experimental results

Fig. 3 shows the internal dryer temperature, ambient air (outside dryer) temperature and the relative humidity inside the dryer for case I (natural ventilation) while Fig. 4 shows the associated weight of clothes[1] recorded over the drying period. The same performance parameters for case II (forced-ventilation) are plotted as shown in Figs. 5 and 6.

Fig. 7(a) and (b) above show the comparison plots of cloths weight reduction and moisture removal vs. drying time respectively. Forced-ventilation method is found superior as it has

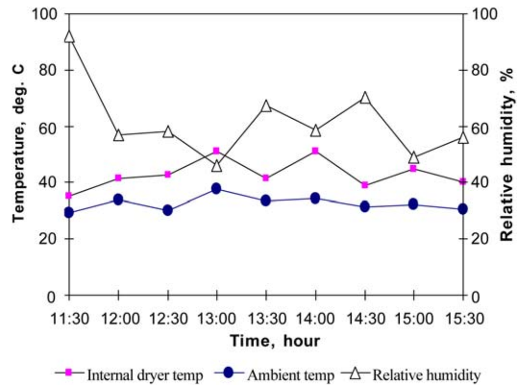



Fig. 3. Temperatures and relative humidity over time for case I (natural ventilation).

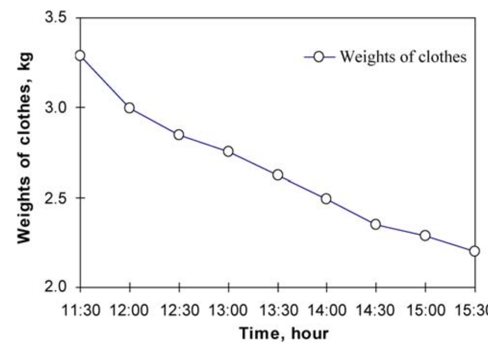



Fig. 4. Weight of clothes[1] with respect to time for case I (natural ventilation).

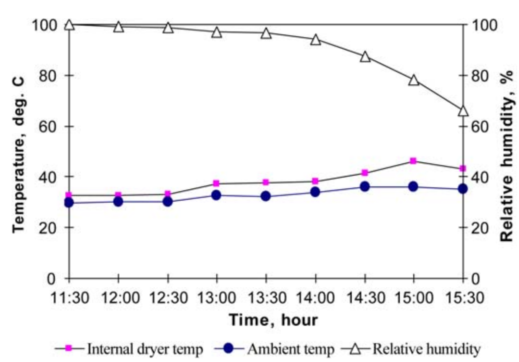



Fig. 5. Temperatures and relative humidity over time for case II (forced-ventilation).

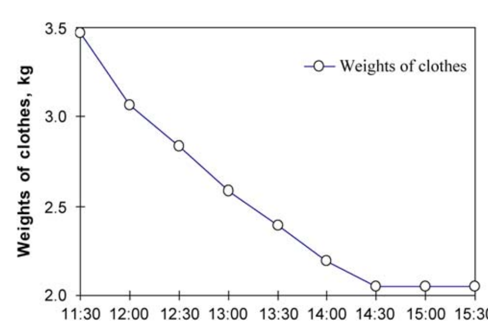
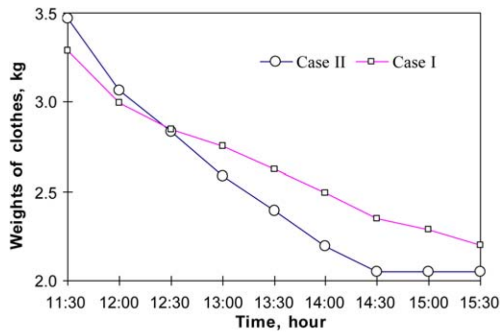
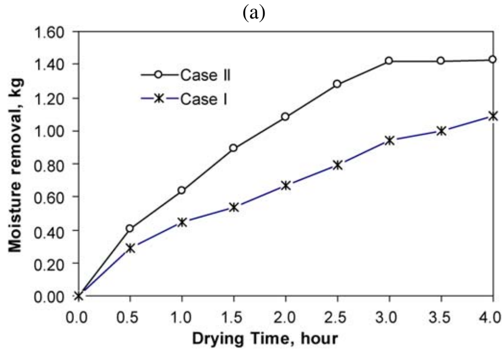



Fig. 6. Weight of clothes[1] with respect to time for case II (forced-ventilation).

[1] Total weight of clothes + hanger + weighting balance.




(a)




(b)

Fig. 7. (a) Weight of clothes[1] with respect to time; (b) Moisture removal vs. drying time.

higher weight reduction right from the beginning of the experiment, as shown on Fig. 7(a). The clothes dried earlier at around 14:30 pm as no significant weight reduction thereafter. Fig. 7(b) further shows that moisture removal rate is more effectively achieved by forced-ventilation.

## 4. Computational work: thermal transient simulation and results

### 4.1. Thermal transient simulation

For the simulation part, airflow modeling as described in Flovent [19] and Siegal and Howel [20] had been utilized to solve the classic Navier–Stokes equations by superimposing many hundreds or thousands of grid cells which describe the physical geometry of the air flow and heat transfer, i.e.

$$\frac{\partial}{\partial t}(\rho\varphi) + \nabla\big(\rho v\varphi - \psi^{\varphi}\nabla\varphi\big) = S^{\varphi}$$

$$[\text{transient}] + [\text{convection}] - [\text{diffusion}] = [\text{heat source}] \tag{3}$$

The simultaneous equations thus form are solved iteratively for each one of these cells to produce a solution which satisfied the conservation law of mass, momentum and energy. As a result, the flow in any part of the attire dryer can be traced simultaneously coloring the airflow according to another parameter such as temperature and heat flux.

*Governing equations.* The transport equations for mass conservation, momentum and energy are defined in Eq. (4) through Eq. (6) as follows [19,20]:

*Continuity*:

$$\frac{\partial\rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = 0 \tag{4}$$

*Momentum*:

$$\frac{\partial(\rho v_i)}{\partial t} + \frac{\partial(\rho v_i v_j)}{\partial x_i} = -\frac{\partial P}{\partial t} + \frac{\partial \tau_{ij}}{\partial x_i} \tag{5}$$

*Energy*:

$$\frac{\partial}{\partial t}(\rho c_p T) + \frac{\partial(\rho c_p T)}{\partial x_i} = \frac{\partial}{\partial x_i}\left(k\frac{\partial T}{\partial x_i}\right) + \frac{\partial p}{\partial t} + \frac{\partial p}{\partial x_i} \tag{6}$$

Heat flux due to solar radiation (Flovent [19]) is expressed as follows:

$$Q_k = \varepsilon_k A_k \sum_{j=1}^{N} G_{jk}\sigma\big(T_j^4 - T_k^4\big) \tag{7}$$

Where $Q_k$ is the net heat-flux arriving at the surface $k$ for a general system of $N$ radiant surfaces; $G_{jk}$ is the proportion of radiative energy emitted by surface $k$ that makes its way to surface $i$ by all possible routes.

The boundary surfaces assumed and considered in the present study are: (a) smooth, zero slip wall (b) pressure-based inlet and (iii) fan outlet. Water vapor is modeled as a contaminant in air with molecular diffusivity of $2.6 \times 10^{-5}\ \text{m}^3\,\text{s}^{-1}$ and its density follows ideal gas law.

An initial study based on the above finite volume method coupled with radiation–ventilation module was employed to simulate the internal airflow of the dryer. For the current paper, the following are considered, namely (a) mass flow and heat transfer, (b) solar radiation and (c) heat flux and forced-ventilation due to fan; and (d) transient state simulation.

### 4.2. Simulation results

#### 4.2.1. Temperature rise visualization

An example of the initial simulation results under natural ventilation conditions is shown in Fig. 8(a) and (b). Fig. 8(a) shows the initial internal temperature profile developed after 10 minutes while Fig. 8(b) shows the temperature profile at an elapse time of 180 minutes. It can be clearly seen that much higher temperature distribution had been buildup over the period.

#### 4.2.2. Validation with experimental works

Comparison plots of internal temperature and humidity vs. time, for both experiment work (solid line) and computational work (dashed line) under forced-ventilation, is given in Fig. 9(a). The plot of moisture removal with time, for both experiment and computation work, is as shown in Fig. 9(b). The graphs show that results from experiment work came close to the simulation works. Cloths weight reduces with temperature rise and amount (concentration) of moisture removal.

#### 4.2.3. Parametric study

The aim of the parametric study is to investigate the feasibility of employing higher capacity fans, i.e. higher forced-ventilation rates, on thermal buildup or energy stored if the current system operated under same ambient weather conditions,

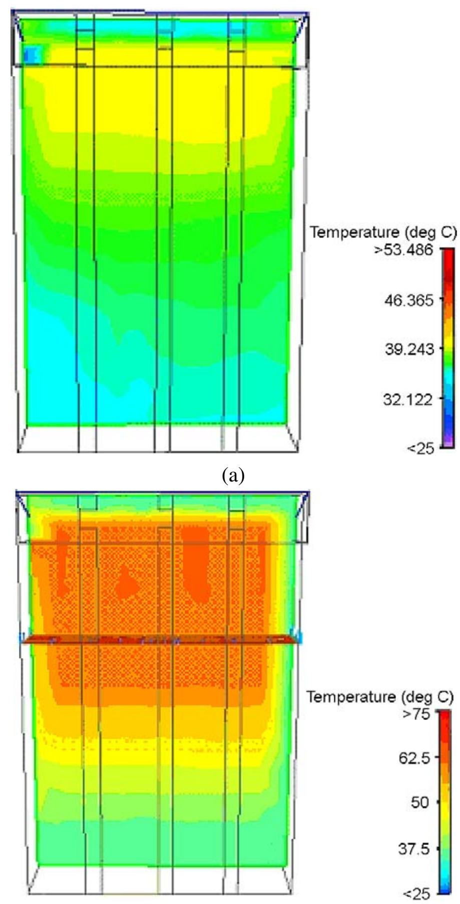



Fig. 8. (a) Temperature profile simulated at initial time, $t = 10$ minutes; (b) Temperature profile developed at time, $t = 180$ minutes.

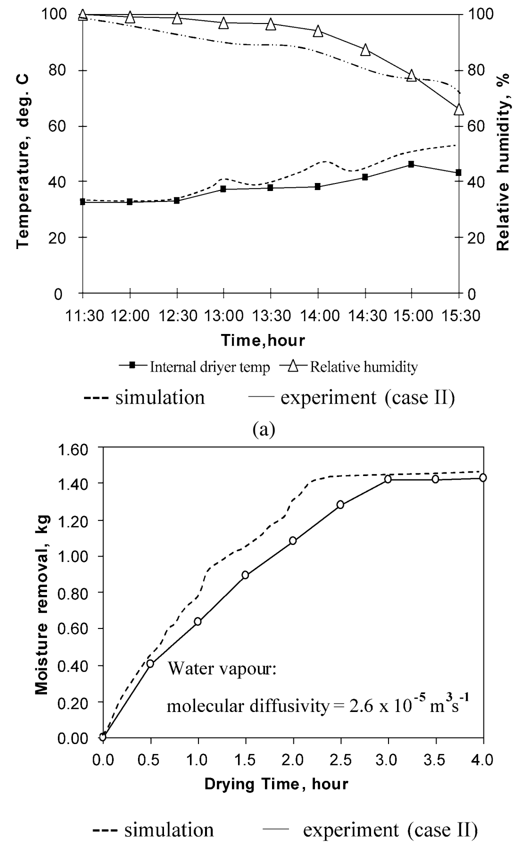



Fig. 9. (a) Comparison plots of internal temperature and humidity under forced-ventilation; (b) Comparison plots of moisture removal rate under forced-ventilation.

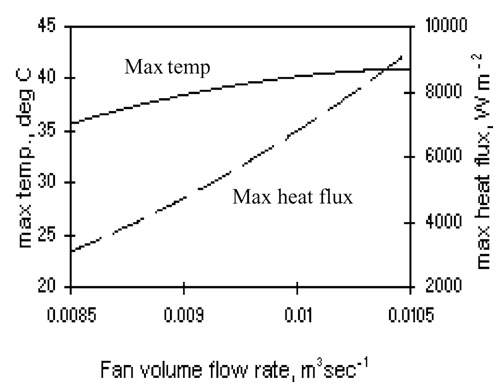



Fig. 10. Maximum internal attire temperature and heat flux as a function of fan volume flow rate (molecular diffusivity = $2.6 \times 10^{-5}$ m$^3$ s$^{-1}$, time $t = 30$ minutes).

especially at initial drying time. This is done by simulating a range of fan volume flow rates which vary from 0.0085 m$^3$ s$^{-1}$ to 0.0105 m$^3$ s$^{-1}$. The parameter range corresponds to approx. 2.4 to 3.0 air change per minute (*ACM*). A typical result obtained at $t = 30$ min is as shown in Fig. 10. The result shows that higher rate of forced-ventilation could improve the temperature and buildup of heat flux under similar ambient conditions.

## 5. Discussion of result

### 5.1. Experimental study

The hand-squeezed clothes were successfully dried in the attire dryer within 3 hours, compared to about 5 to 7 hours needed for the conventional cloth lines drying under local conditions. The low drying rate by using cloth line was due the fact that the locality is having high humidity of around 80–85% and poses low wind speed.

The temperature range of the internal drying air is around 35–55 °C in both the cases studied. Comparison study had shown that the attire dryer with forced-ventilation had superior drying rate and better moisture removal efficiency (Fig. 7(a) and (b)) as compared to natural ventilation. The moisture retention in the cloths for case I was high, as a result the internal humidity profile was shown quite static (see Fig. 3) due to poor ventilation and low wind speed from outdoor into the dryer. Insufficient amount of air change retarded moisture removal through the dryer and the clothes' surface ultimately lead to slow moisture removal.

The increase of drying performance in terms of cloth weight reduction and moisture removal as shown in Fig. 7(a) and (b) respectively may be due to increase of pressure difference ($\Delta p$). This is because $\Delta p$ increases with air flow (forced-ventilation) apart from temperature difference ($\Delta T$) due to solar radiation. The potential difference thus speeds up the separation

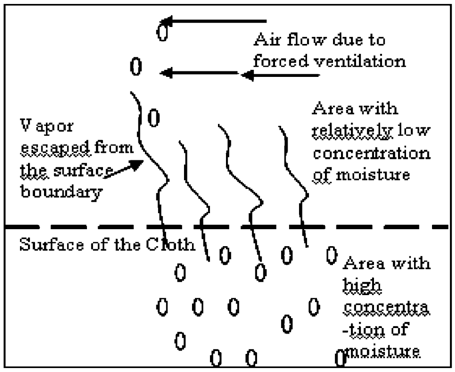



Fig. 11. Simplified drying mechanisms that occurs on the surface of the cloth with forced-ventilation.

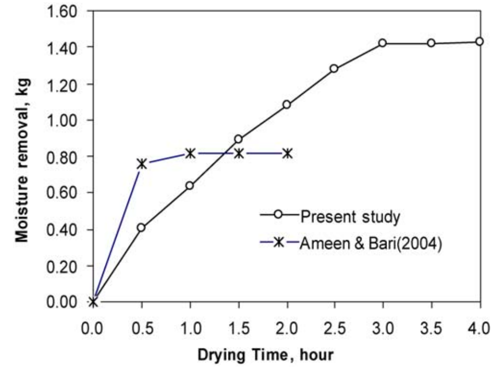



Fig. 12. Comparison study of moisture removal vs. drying time.

process in between the moisture and the cloth surface through enhancement of evaporation, convection and diffusion. Therefore, higher percentage of water vapor escaped quickly form the boundary surface of the cloth due to relatively lower concentration of moisture at immediate vicinity surrounding the cloth which exposed to the fast moving air flow (Fig. 11). This causes higher internal humidity in the dryer initially as shown in Fig. 5. However, these escaped moisture or vapor continuously removes from the dryer by forced-ventilation. As a result, total cloth drying time is reduced.

A review on the past work has shown that the present drying method assisted with forced-ventilation poses equivalent average moisture removal rate (0.43 $\mathrm{kg\,h^{-1}}$) compared to that reported by Ameen and Bari [9] where waste heat from air conditioning (average moisture removal rate $= 0.42$ $\mathrm{kg\,h^{-1}}$) and a commercial cloth dryer were used for drying respectively, as shown in Table 4. Nevertheless, present study took longer complete drying time of 3 hours compared to 2 and 2.5 hours by waste heat and the commercial dryer respectively. Waste heat drying method has the advantage of higher removal rate at initial testing period and shorter drying time, as presented in Fig. 12. This further confirms that result from the present study could be possibly improved by increasing the internal temperature and amount of moisture removal, particularly at initial drying period.

### 5.2. Simulation study

#### 5.2.1. Discussion on the temperature rise visualization

Consistent with the experiments results, the computational results shows quite well the internal temperature rise pattern.

Table 4
Drying performance comparison

| Drying method | Average drying rate, kg $\mathrm{hour^{-1}}$ | Total drying time, hour |
|---|---|---|
| Waste heat from air conditioning[a] | 0.42 | 2 |
| Commercial cloth dryer[a] | 0.52 | 2.5 |
| Present study | 0.43 | 3 |

[a] Ameen and Bari [9].

Fig. 8(a) shows that at $t = 10$ minute, the initial temperature profile was not much different with that of the ambient, with temperature around 35 °C. The highest temperature (yellowish) region, initially only found at the upper portion of the dryer. But gradually the temperature was buildup with time. After 180 minutes, about 60% of the upper potion of the attire area was having a temperature of around 40–50 °C or more due to heat flux generation, as shown in Fig. 8(b).

#### 5.2.2. Discussion on the simulation results compared with experimental findings

The simulation results obtained from the forced-ventilation study came close to that of the experiment works: As shown in Fig. 9(b), the moisture removal or cloth drying prediction was found fairly well-matched to that of the experimental works, although the experiment result (case II) has some what lower drying efficiency performance after approx. 30 mins or 1 hour. The appearance of some clouds perhaps caused the reduction of the drying rate under actual experimental condition. This explanation collaborates with Fig. 9(a) where the actual internal temperature developed was less than that simulated from computational work. Reduction in solar radiation causes a loss in energy absorbed as well as lower ventilation rate and internal thermal energy buildup. Consequently, less moisture movement, fairly steady humidity profile, and higher humidity contents was observed experimentally as depicted in Fig. 9(a).

#### 5.2.3. Discussion on the parametric study and recommendation for further works

The aim of the parametric study reported herein is solely to provide "what-if" situations, i.e. to predict what will happen to the internal temperature and heat flux if different higher fan capacities are employed, under similar ambient weather conditions. The computational result obtained from parametric study in Section 4 shows that temperature and heat flux increases gradually with higher ventilation rates, under similar ambient conditions. At a higher ventilation rate of 0.0105 $\mathrm{m^3\,s^{-1}}$ (2.4 *ACM*), the dryer achieves around 41 °C of internal heat generation and heat flux of approx. 8300 $\mathrm{W\,m^{-2}}$. Only about 36 °C of internal temperature with associated heat flux of 3200 $\mathrm{W\,m^{-2}}$ is found at a lower ventilation rate of 0.0085 (3.0 *ACM*). The range of temperature variation in this particular run is about 5 °C. These preliminary findings underline the importance of high ventilation rate particularly in the early period of drying, and this needs further experiment tests. Since the ambient weather condition changes from day to day, outdoor experimental testing at different day (with *same* or similar ambient conditions but with different fan sizing) would be quite tedious. Such study, however, could be best carried out at laboratory-controlled settings to represent the ambient conditions for a typical day required for study. An optimization study to investigate the primary influencing parameters affecting the system would also be very worthwhile.

## 6. Conclusions

A solar attire dryer had been successfully designed, constructed and tested in the present study. Coupled with forced-ventilation (case II), the solar drying performance achieved an average drying rate of $0.43\ \mathrm{kg\,h^{-1}}$ and drying time of 3 hours in a typical day, even under local high ambient humidity of around 85% and at very low outdoor wind speed. The experimental results had been discussed and compared based on two scenarios: (A) natural ventilation vs. forced-ventilation and (B) forced-ventilation (case II) vs. waste heat drying from air conditioning [9]. The experimental comparison studies show that the present forced-ventilation system (case II) offer better performance compared to natural ventilation (case I) and equivalent in performance to that of waste heat drying method although it has longer completion drying time of 3 hours. Therefore, it can be deduced that more airflow and heat flux is important especially in the early stages of drying to further remove free moisture around the clothes' surface.

From the computational flow study, the simulation of the attire dryer thermal transient demonstrates the model's capability and yields sensible results. Both experimental and simulation work conducted has shown that cloth drying rate increases with temperature rise, heat flux and moisture removal. Apart from the ease of visualization, the computer simulation and parametric study presented in the preceding sections was developed to assist in understanding the experimental findings, and suggest for future works.

Three of the main conclusions from the present study can be drawn as follows:

- The present drying method, i.e. solar attire dryer assisted with forced-ventilation (case II), has higher ventilation rate of $0.43\ \mathrm{kg\,h^{-1}}$ and shorter completion drying time of 3 hours compared to natural ventilation (case I) which has a drying rate of $0.25\ \mathrm{kg\,h^{-1}}$ and completion drying time of more than 4 hours. This is because heat flux generation and moisture removal increase with ventilation rate.
- The present drying method assisted with forced-ventilation (case II) has almost equivalent average moisture removal rate of $0.43\ \mathrm{kg\,h^{-1}}$ compared to the method of using waste heat from air conditioning ($0.42\ \mathrm{kg\,h^{-1}}$) and a commercial dryer. However, present method takes longer drying completion time of 3 hours compared to 2 and 2.5 hours by waste heat and the commercial dryer respectively.
- Heat flux buildup and drying performance of the solar attire dryer could possibly be further enhanced with higher fan volume flow rates and low *ACM*, especially at initial drying period.

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## References

[1] O.V. Ekechukwu, B. Norton, Review of solar-energy drying systems II: an overview of solar drying technology, Energy Conversion and Management 40 (6) (1999) 615–655.
[2] J.W. Sutherland, Batch grain drier design and performance prediction, J. Agriculture Engineering Research 20 (4) (1975) 423.
[3] B. Kilkis, Solar energy assisted crop and fruit drying systems: theory and applications, in: F. Vogt (Ed.), Proc. Sem. Energy Conserv. & Use of Solar and Other Renewable Energies in Bio-Industries, 1981, pp. 307–333.
[4] M. Condorí, R. Echazú, L. Saravia, Solar drying of sweet pepper and garlic using the tunnel greenhouse drier, Renewable Energy 22 (4) (2001) 447–460.
[5] H.C. Van Deventer, Feasibility of energy efficient steam drying of paper and textile including process integration, Appl. Thermal Engrg. 17 (8–10) (1997) 1035–1041.
[6] J. Adnot, Metal fibre burners in industrial equipment, Fuel Energy Abstracts 36 (5) (2000) 355.
[7] A.S. Majumdar, Mujumdar's practical guide to industrial drying, Energex Corporation, Montreal, 2000.
[8] K. Klöcker, E.L. Schmidt, F. Steimle, A drying heat pump using carbon dioxide as working fluid, Drying Technol. 20 (8) (2002) 1659–1671.
[9] A. Ameen, S. Bari, Energy Conversion and Management 45 (9–10) (2004) 1397–1405.
[10] G.W. Ingram, Solution of grain cooling and drying problems by the method of characteristics in comparison with finite difference solutions, J. Agriculture Engineering Research 24 (3) (1979) 219–232.
[11] T. Togrul, D. Pehlivan, Mathematical modelling of solar drying of apricots in thin layers, J. Food Engineering 55 (3) (2002) 209–216.
[12] E. Torres-Reyes, J.J. Navarrete-Gonzalez, B.A. Ibarra-Salazar, Thermodynamic method for designing dryers operated by flat-plate solar collectors, Renewable Energy 26 (4) (2002) 649–660.
[13] G. Gopalnarayanan, R. Radermacher, Heat pump assisted dryer using refrigerant mixtures—batch mode drying, ASHRAE Trans. 2 (1997) 888–895.
[14] C.Y. Lam, Design and construction of attire dryer for high-rise building, BEng Final Year Project Report, May, 2004, Universiti Malaysia of Sarawak, 2004, pp. 73–84.
[15] H. Oman, Energy Systems Engineering Handbook, Prentice-Hall, Englewood Clifts, NJ, 1997.
[16] W.F. Stoecker, J.W. Jones, Refrigeration and Air Conditioning, second ed., McGraw-Hill Book Company, Singapore, 1982.
[17] R.H. Howel, H.J. Sauer, W.J. Coad, Principles of Heating, Ventilating and Air Conditioning, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, 1998, pp. 7.6–7.24.
[18] F.A. Mikie, Advance study of solar-attire dryer, BEng Final Year Project Report, June, 2005, Universiti Malaysia of Sarawak, 2005, pp. 59–67.
[19] Flovent Software Manual, 2004, Version 4.3, Flomerics UK Ltd, United Kingdom.
[20] R. Siegal, J.R. Howel, Thermal Radiation Heat Transfer, third ed., Hemisphere, New York, 1992 (Chapter 7).