A New Physics-Based Drying Model of Thin Clothes in Air-Vented Clothes Dryers

Taeil Yi, Joshua C. Dye, Molly E. Shircliff, and Farhad Ashrafzadeh

***Abstract*—A new physics-based model for the drying process is introduced, capable of accounting for both fabric sizes and types. This is achieved by using the probability function and the latent heat of the water at a given temperature. Furthermore, the dependence of drying efficiency on various drying load sizes is discussed and a new interpretation of drying efficiency, called normalized drying efficiency, is presented. This allows coherent and meaningful comparison of the process efficiency across various load sizes and cycle times. Finally, percolation theory is introduced to explain qualitatively the effect of clothes load sizes on the drying process. This is achieved through determining the probabilities of a volume ratio (vacant volume per total drum volume), which is the probability of the interaction between the clothes loads and hot air flow in the clothes dryer. The model is validated using both experimental and literature data and is now being used for the development of an energy efficient moisture removal process, which is essential to the design of next-generation energy efficient clothes dryers.**

***Index Terms*—Clothes dryers, drying modeling, mass and energy conversation, percolation theory, process modeling.**

I. Introduction

WHILE energy resources are limited, energy consumption continues to increase every year. Based on statistics provided by the United States Department of Energy (DOE), about 22% of total generated electricity at national level is consumed by residential loads [1]. This amount is rapidly increasing due to population growth and socioeconomic improvement, as well as ever-growing product electrification. Furthermore, while the energy consumed for space heating has declined over time, appliances and lighting have shown a steady growth in energy consumption since 1984. If this trend continues and no energy efficiency improvement is made, we will need 40% more energy to meet our needs by 2030 [2]. This will have a significant adverse impact on both depleting resources and the environment in which we live. For these reasons, we have decided to develop the next generation of energy efficient and eco-friendly appliances. Because the clothes dryer is one of the primary energy sinks among electric appliances, we started our research with clothes dryers. A typical electric clothes dryer consumes about 1 MWh per year, making it the second largest consumer of electricity among household appliances in the United States [1]. The Environmental Protection Agency estimates that all residential clothes dryers in the U.S. annually consume around 43 million MWh of electricity and 44.5 trillion BTUs of natural gas, leading to carbon dioxide emissions of 32 million metric tons [3]. Thus, improving the efficiency of clothes dryers will greatly reduce both environmental pollution and household energy waste.

Two primary tasks are planned to be accomplished at this initial stage of the project: The first step consists of developing an advanced research test bed for the clothes dryer with full observability and increased controllability of state variables. The test bed should also have the capability of real-time control and data acquisition. We selected the air-vented residential dryer for the research because according to the U.S. DOE, around 80% of households in the United State use air-vented dryers [4]. Temperature, humidity, and mixing ratio (the ratio of mass of water vapor to the mass of dry air) are measured both at inlet and exhaust of the dryer with a resolution of 1 sample per second. The next step is to develop a physics-based model for the drying process and validate the proposed model using the above test bed.

In most studies, the research approach taken has been either purely empirical (data-based) or semiempirical, without understanding the underlying physical principles of the drying process and the tradeoffs among various performance criteria. Ng and Deng have developed a model for the clothes drying process based upon which a new control method has been proposed to automatically terminate the drying cycle using moisture content in ambient environment [5]. However, the model is only a semiempirical and it covers only the last two parts of the drying cycle, i.e., constant rate and falling rate instead of entire drying cycle, which includes heat-rise phase as well. Tranxuan and Deans utilized the modified convective transport equation to calculate the mass transfer at air–clothes interface [6]. Haghi *et al.* employed Nordons mathematical model with the rate equation for mass transfer between the moisture in the fabric materials and the air moisture in the fabric pores [7], [8].

However, neither of them showed a clear picture of the moisture condition on the clothes' surfaces. Lambert suggested the water activity to quantify this moisture condition based on the water content in the clothes [9]. Deans substituted Lamberts

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expression to improve his drying model but the expression was based on a mathematical approximation of the sorption-isotherm curve fitting—hence data based [10]. Delshad and Thomas proposed a model for drying wood which predicts the time-dependent moisture content and temperature of timber inside a drying kiln [11]. Although the model is more physics-based, it does not take into account the water activity level as proposed in our paper.

Viewing the drying process in the context of percolation theory, to the best knowledge of the authors, is novel and it promises a great potential for future research in this area. Percolation theory has brought a new and much deeper understanding of various phenomena and properties in material sciences and physics [12]. Among many applications of percolation theory, porous media problems have perhaps received the greatest attention [12]–[16]. Clothes are porous materials in nature. Therefore, modeling the reaction and diffusion of these porous materials using percolation theory can bring new insight to the underlying phenomena in the drying process. This can potentially lead to identify more energy efficient drying processes, which is the next phase of our research.

This paper has been organized as follows: After an introduction in Section I, the development of an advanced research test bed is explained in Section II. This test bed consists of a data acquisition, signal processing, and real-time control modules. These features enable hardware-in-loop capability of the test bed. Section III presents a detailed derivation of the governing equations of the drying process based on physics. Section IV represents the model validation and discussion of the effect of various loads. It also introduces a qualitative interpretation using the percolation theory. Concluding remarks follow in Section IV.

In this paper, we propose a novel approach to describe the water activity based on underlying physics. We accomplished this using the laws of mass and energy conservation as well as those of convection mass transfer in (6) and (7). We also propose a new technique to improve the model prediction using percolation theory. Viewing the drying process in the context of percolation theory improves model prediction, explaining the discrepancy in energy efficiency in this process from one load to another. As seen in Section V, percolation theory predicts why the drying efficiency decreases beyond the threshold load due to the effective air path.

II. Test Bed Development

To transform the production dryer into an advanced laboratory test bed, sensors had to be installed at the inlet and the exhaust of the drum so that an accurate description of the input and output air could be measured and recorded for validation purposes. These air characteristics include temperature and mixing ratio. Next, to have full control over the drying process, the dryer controller board was bypassed and a controllable switch was used to control the dryer's heater coil. The controllable switch was used to regulate the input temperature at the inlet of the drum. The switching logic was designed by observing the real-time values of inlet temperature. To replicate the original drying cycle by the dryer, an ON/OFF hysteresis control logic was used by the new controller. Fig. 1 shows the experimental setup and Fig. 2 depicts the block diagram of the developed test bed including sensors, actuators, and real-time data acquisition and control system.

Fig. 1. Experimental setup for model development and validation.

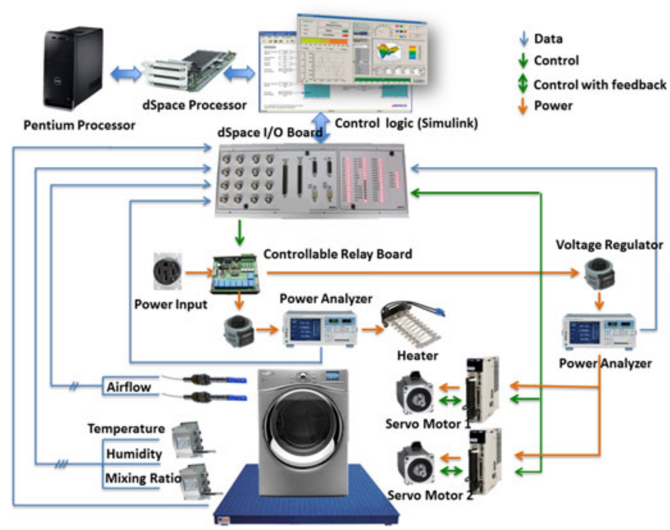

Fig. 2. Block diagram of the advanced test bed for an air-vented cloth dryer including sensors, actuators, and the real-time data acquisition and control system using dSPACE 1103.

The sensors were chosen to measure key state variables such as temperature, clothes moisture, and mixing ratio in the drying process. Temperature was measured for both inlet and outlet of the dryer as well as the clothes fabrics. The temperature of the clothes was found using an infrared thermometer. Changes in moisture were viewed through the use of absolute humidity and mixing ratio sensors at the drum's inlet and outlet. Special care had to be taken in selection of both inlet and the outlet humidity and temperature sensors. Due to the high temperature (and low moisture) at the dryers inlet and high humidity (at low temperature) at its outlet, both sensors were chosen specifically to withstand the harsh conditions. A scale was used to

TABLE I
LIST OF HARDWARE MODELS

	Model
Dryer	Electric air-vented dryer #WED86HEBW
DAQ system	dSPACE 1103
Sensor-set 1	Vaisala HMT335 for ω & T measurement
Sensor-set 2	Vaisala HMT337 for ω & T measurement

DAQ stands for data acquisition, ω is the mixing ratio, and T is temperature.

Fig. 3. Schematic diagram of the drum and the clothes. i and e represent the inlet and the exhaust. Wave arrows show the energy transfer and two thick arrows at the inlet and the exhaust mean the thermal energy input and the rest of thermal energy.

measure the load weight and through which the moisture level was calculated in real time.

In order to acquire sensor data for online and offline data processing, the dSPACE controller (DS1103 board) was used. dSPACE is a real-time data acquisition and control system with a dedicated processor and fully reconfigurable, hence flexible interface (input/output) capabilities. dSPACE acquires sensor data directly into MATLAB's workspace and uses Simulink as the programming environment for embedded control. This greatly accelerates and simplifies process monitoring and control in real time. Table I shows the model numbers for the key components in the test bed.

III. Physics-Based Modeling of the Drying Process

One of the primary tasks of this project is to establish the physics-based model of the drying process to predict thermodynamic parameters and variables based on fundamental science and engineering knowledge. Consider a dryer drum as a control volume for modeling (see Fig. 3). The clothes and humid air stay in the drum and the air flow enters the inlet and leaves through the outlet. Our modeling approach to this problem consists of defining a detailed heat and mass transport equation which is described as follows.

First, we start with the law of energy conservation, which explicitly describes the energy entering at the inlet (E_{inlet}); energy leaving at the exhaust (E_{exhaust}); the net energy transfer (Q_{NET}); the energy consumed for phase change; and the energy stored in the drum, the clothes, and the water in the clothes [17]. The work due to the motion of the drum and the clothes is not considered explicitly at this stage. If we assume that the drum, the clothes, and the water in the clothes have the same temperature as the clothes temperature (T_{cl}), the first principle of thermodynamics is given by

$$0 = \dot{E}_{\text{inlet}} - \dot{E}_{\text{exhaust}} - \sum_i c_{p,i} m_i \dot{T}_{\text{cl}} + \dot{Q}_{\text{NET}} \tag{1}$$

where the difference between the rate of change of energy entering at the inlet, which is delivered by the dry air, and the rate of change of energy leaving at the exhaust, which is the energy produced by heat transference of the moisture in the wet clothes, is calculated by the enthalpy difference at the inlet and the exhaust. With assumptions of constant rate of change of air mass and no contribution of gravity, the rate of change of the energy stored in the ith material is given by the product of the specific heat ($c_{p,i}$), mass (m_i), and the rate of change of a temperature ($\dot{T}_{\text{cl}}$). The material index i represents fabric, steel, and water. The rate of change of the net energy transfer ($\dot{Q}_{\text{NET}}$) is given by a function of the temperature difference between the drum and the ambient air. Thus, (1) can be replaced as

$$\begin{aligned} 0 = \ & \dot{m}_{\text{air}} h_{\text{inlet}} - \dot{m}_{\text{air}} h_{\text{exhaust}} - \sum_i c_{p,i} m_i \dot{T}_{\text{cl}} \\ & + h^*_{\text{NET}} A^*_{\text{NET}} (T_{\text{cl}} - T_{\text{ambient}}) \end{aligned} \tag{2}$$

where h_{inlet} and h_{exhaust} are enthalpy values at the inlet and the exhaust and $\dot{Q}_{\text{NET}}$ is expressed as the convection heat transfer with the energy transfer coefficient h^*_{NET} and the effective area A^*_{NET}. The mass of the water content is given by the mass transport equation. The enthalpy difference between the inlet and the exhaust can be expressed alternatively as

$$h_{\text{inlet}} - h_{\text{exhaust}} = c_{p,\text{air}} (T_{\text{inlet}} - T_{\text{exhaust}}) + \epsilon \tag{3}$$

where ϵ is energy necessary for the phase transition and also the energy stored in the vaporized water in the air. This ϵ value is relatively small compared to the other terms. Thus, it is neglected and the final expression is given by

$$\begin{aligned} 0 = \ & \dot{m}_{\text{air}} c_{p,\text{air}} (T_{\text{inlet}} - T_{\text{exhaust}}) - \sum_i c_{p,i} m_i \dot{T}_{\text{cl}} \\ & + h^*_{\text{NET}} A^*_{\text{NET}} (T_{\text{cl}} - T_{\text{ambient}}). \end{aligned} \tag{4}$$

The drying process is governed by a mass transfer of the water in the clothes. The fundamental physics of the water vapor transfer is due to both 1) the mass diffusion generated by the existence of the concentration gradient between the clothes and the bulk air and 2) the convective mass transport based on the fluid motion. The reference governing equation starts with the convective transfer to describe the mass diffusion transport because the primary transport phenomena occur due to the convection. The rate of change of water removed from the clothes is expressed by a function of the humidity difference between the surface of the clothes and the bulk air humidity as

$$-\dot{\chi} = K^*_{\text{MT}} A^*_{\text{MT}} \left(\omega^{\text{surf}}_{w,\text{air}} - \omega_{w,\text{air}} \right) \tag{5}$$

where χ is the water content in the clothes, K^*_{MT} is the mass transfer coefficient, A^*_{MT} is the effective area of the mass transport, $\omega^{\text{surf}}_{w,\text{air}}$ is the mixing ratio of the thin air layer adjacent to the surface of clothes, and $\omega_{w,\text{air}}$ is the mixing ratio of the bulk air, the quantity is assumed to be the same as the average of the

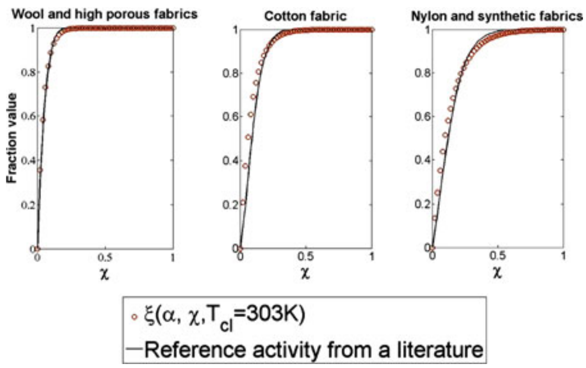

Fig. 4. Fraction value of $\xi(\alpha,\chi,T_{\rm cl})$ versus χ when the clothes temperature ($T_{\rm cl}$) is at 303 K. α varies depending on the fabric type of clothes.

two mixing ratio values at the inlet and the exhaust [18]. In this paper, we target the thin clothes to ignore the time-dependent heterogeneous water distribution inside the clothes by diffusion due to the nonignorable clothes thickness. Various factors such as temperature, clothes types, convection flow velocity, the quality of mixing of dry air and water vapor, the tumbling motion of clothes, drum geometry, and the clothes packing level affect the diffusive mass transport coefficient. We approximate $K^*_{\rm MT}$ using the Lewis number (Le), which is the ratio of thermal diffusivity to mass diffusivity.

$\omega^{\rm surf}_{w,\rm air}$ is calculated indirectly by quantification of the amount of water in the clothes that has been evaporated directly due to excess latent heat. Tranxuan and Deans used the generic form of the mass transfer at the air–clothes interface and assumed that $\omega^{\rm surf}_{w,\rm air}$ was the mixing ratio of saturated air at $T = T_{\rm cl}$ [6]. However, humidity on the surface of the clothes is not the same as the humidity of the air layer adjacent to the clothes. Deans employed the Lambert's expression to describe the fraction of humidity at the state of isotherm as a function of water content and material properties [9], [10]. However, this expression is based on the regression of experimental data.

Instead, we suggest the form of $\omega^{\rm surf}_{w,\rm air}$ based on the probability function. This function uses the Boltzmann constant to explain underlying physics using experimental data. The first step is to quantify the amount of nonevaporated water in the clothes $m^{\rm no-evap}_{w,\rm cl}$ as

$$\begin{aligned} m^{\rm no-evap}_{w,\rm cl}(\alpha,\chi,T_{\rm cl}) &= m^{\rm max}_{w,\rm cl}\xi(\alpha,\chi,T_{\rm cl}) \\ \xi(\alpha,\chi,T_{\rm cl}) &= 1-\exp\left(-\frac{\alpha\chi\epsilon_{\rm LH}}{k_B T_{\rm cl}}\right) \end{aligned} \tag{6}$$

where $m^{\rm max}_{w,\rm cl}$ is the maximum amount of water in the clothes, $\xi(\alpha,\chi,T_{\rm cl})$ is the activity coefficient, α is the property parameter to characterize the type of clothes fabrics, $\epsilon_{\rm LH}$ is the latent heat of vaporization, and k_B is the Boltzmann constant [12]. For the adjacent air film, the amount of water in the air cannot exceed its saturated value. Thus, the $\omega^{\rm surf}_{w,\rm air}$ can be given by the following inequality as:

$$\begin{aligned} m_{\rm air}\omega^{\rm surf}_{w,\rm air} &= \gamma m^{\rm no-evap}_{w,\rm cl}(\alpha,\chi,T_{\rm cl}) \\ &= \gamma m^{\rm max}_{w,\rm cl}(T_{\rm cl})\xi(\alpha,\chi,T_{\rm cl}) \\ &\geq m_{\rm air}\omega^{\rm sat}_{w,\rm air}(T_{\rm cl})\xi(\alpha,\chi,T) \end{aligned} \tag{7}$$

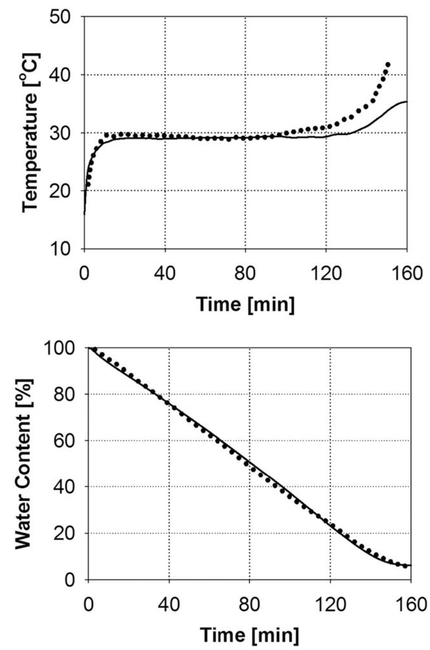

Fig. 5. Comparison of the time-dependent clothes water content (a) and clothes temperature (b) between the literature data and our simulation results. The literature datasets are shown in dot lines and our simulation results are depicted in solid lines [6].

where γ is the desorption weighting factor at the clothes interfaces and its value is less than 1. $\xi(\alpha,\chi,T_{\rm cl})$ plays the same role as the activity coefficient proposed by Lambert *et al.* [9]. Fig. 4 shows the profile of $\xi(\alpha,\chi,T_{\rm cl})$ in χ at $T_{\rm cl} = 303$ K with appropriate parameters. α varies depending on the type of fabrics. We deduce α values based on the fitting with the activity profiles given in the literature [10].

The solution of the set of the first-order differential equations is calculated by using the Runge–Kutta–Fehlberg algorithm implemented in MATLAB. All simulations are performed on a workstation with two Intel Xeon E5530 2.4 GHz CPUs and 36 GB of memory.

IV. Results and Discussion

A. Model Validation

1) Model Validation With the Literature Data: We compare two selected variables from experiments and a literature data to validate the model suggested in the previous section [6]. The clothes water content and temperature are key state variables in drying process and they are, therefore, selected for the purpose of comparison. Fig. 5 shows the clothes water content and temperature. As shown in the figure, our simulation results based on the physic-based model successfully reproduce the target variables.

2) Model Validation With the Test Bed: Our model is validated with experimental data using two fabric types: 1) a synthetic fabric which is made of 35% cotton and 65% polyester, and 2) 100% cotton fabrics. Fig. 6 represents both clothes water content and temperature for a 3 kg of synthetic fabric in (a) and 2.8 kg of cotton fabric in (b). It is important to note that due to limitation in the sensor resolution of the weight scale, the experimental data shows a step change in data acquired from our

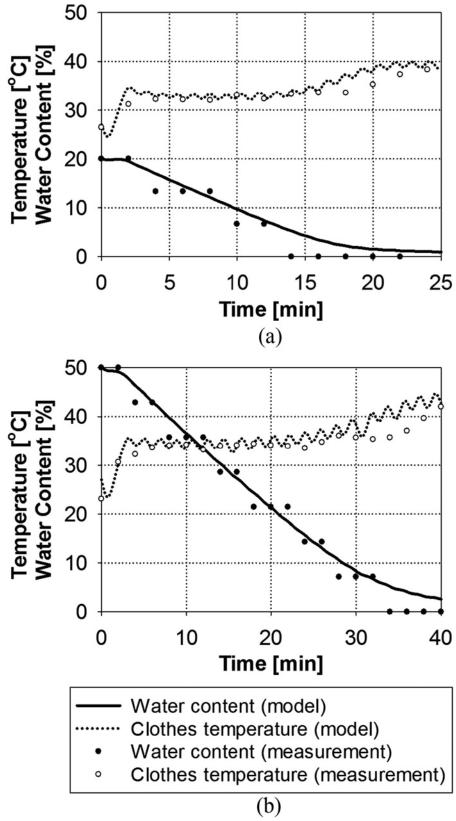

Fig. 6. Comparison of the clothes temperature and water content between the simulation and the experiments for (a) synthetic fabrics and (b) cotton fabrics.

test bed. Apart from this, Fig. 6 indicates our proposed model that predicts the real performance for two different fabric types very well and, therefore, can be used, in future steps, to control algorithm development and energy optimization as originally intended.

B. Effect of Clothes Load

Fig. 7 shows the water content and temperature for cotton fabric. Three different clothes loads are selected out of the load range from 1 to 6 kg. All parameters of these three simulations are set the same except for the clothes weight and their effective area. While the model predicts the drying process for a medium load very well, there is a dependence between simulation and experimental results for both small and heavy loads. In fact, the simulation results depict a slower response for small loads and a faster response for large loads. This implies that our proposed model still includes deficiencies in reproducing the experimental results. To explain these discrepancies for various load sizes, we define a new parameter, called normalized efficiency, as the efficiency per unit of both mass and time, i.e., 1 min. This allows us to compare η meaningful for different load sizes and cycle time. In fact, η is defined as $\eta = (m_{\rm cl} \times \chi(t = 0) \times (\text{unit time}))/((t_{\rm in} - t_{\rm fi}) \times (\text{unit mass})) \times 100$ where t is time. $\eta = 100$ means that 100 g of water content is removed in 1 min. Now as Table II shows that the dryer operation is best when the clothes load is between 2.8 and 4 kg. The hot dried air cannot contact the cloth surfaces effectively for the low load case. One of the reasons why the heavy load case has less efficiency than the medium load case is due to the limitations of the amount of evaporated water and the number of effective air flow paths. In the section, we propose a new technique to improve the model prediction and make it robust against various load sizes. This is achieved using the concept of *Percolation Theory*, which is explained in Section IV-B2.

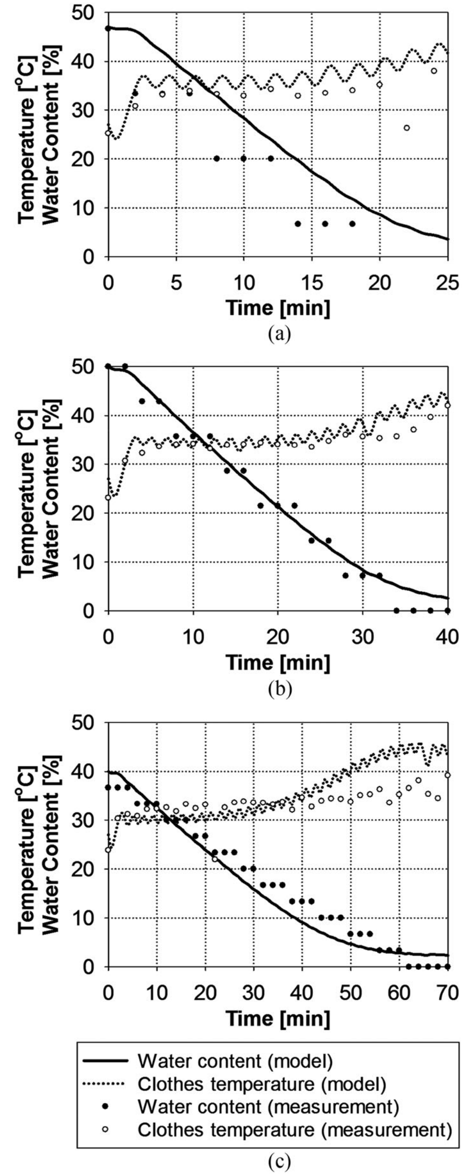

Fig. 7. Comparison of the clothes temperature and the water content of different clothes loads: (a) 1.5 kg, (b) 2.8 kg, and (c) 6 kg.

1) Limitation of the Literature Models Versus Our Proposed Model:

Bassily and Colver introduced the effect of the clothes load and its dependence on the annual operation cost of a dryer [13], [14]. They also showed that the energy cost to dry the lighter clothes would be higher than that of the heavier clothes for the same applied heat power. Although they referred to the effect of clothes load, no physical model was suggested to explain the phenomena. The conventional mass transfer equation

TABLE II
COMPARISON OF THE CHARACTERISTIC PARAMETER η TO REPRESENT THE EFFICIENCY OF DRYING PER MASS AND TIME FOR VARIOUS FABRICS: COTTON, SYNTHETIC, AND TERRY TOWEL

Load [kg]	1.5	2	2.8	4	5	6
η_{Cotton}	36	42	40	51	40	43
$\eta_{\text{Synthetic}}$	–	41	46	48	42	37
η_{Terry}	–	34	46	36	–	34

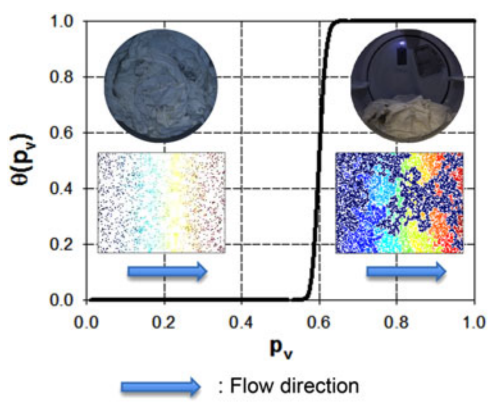

Fig. 8. Percolation probability profile as a function of a probability to occupy the effective air path site. Two subsnapshots show cotton clothes packing in a drum (top) and the air path maps depending on the probability to occupy the effective air path site (bottom). Arrows show the air flow direction.

used the effective area but this parameter was used without considering the geometric constraint, such as the drum volume.

2) Qualitative Interpretation Using the Percolation Theory: The mass transfer process between the clothes and bulk air is caused by both the different amount of the water content in these two volumetric regions and the connectivity of air flow path between the inlet and outlet. We employ the concept of the percolation theory with the volume ratio of vacancy volume to drum volume, ϕ_{VD} [19]. ϕ_{VD} is calculated by the normalized difference value between drum volume and the total effective clothes volume where the normalizing factor is the drum volume. Physically, the effective clothes volume plays a significant role in the drying process because this quantity determines the minimum volume of the air flow path without interruption of the water removal process. This quantity could be estimated by inspection based on experimental data. For a simple qualitative interpretation, we assume that the system domain is represented by the two-dimensional (2-D) lattice and ϕ_{VD} is utilized as the vacancy probability p_v to occupy the lattice site. Then the question is changed to "What is the percolation probability $\theta(p_v)$, or the probability that the clothes occupy the open path to connect from inlet to exhaust?" As shown in Fig. 8, the critical probability p_c, which is the minimum probability value to establish an air path between inlet and outlet, is already well established and its value is about 0.6. In this plot, the x-axis represents the probability to occupy the vacant site and the y-axis shows the percolation probability value. Two additional snapshots in the Fig. 8 shows the air path connecting between the inlet side and the exhaust side and the common colors in the box are used to distinguish the groups with continuously connected sites. If the probability is less than p_c, there rarely exists the effective air flow path in a drum as shown in the left snapshot of Fig. 8. In the case of full clothes packing, many small air pockets would be generated in a drum. As the probability value increases and gets close to the critical probability, a channel to connect from inlet to the outlet side could be generated more frequently (see the dark blue area in the right-side snapshot of the Fig. 8). The large vacancy probability case, which requires delicate treatment of clothes conformations in a drum, for a small load case, is not interpreted using this idea because our interest focuses on the heavy load case. As a result, we observed that the system would have less effective air path when the clothes are packed in the machine fully. This also means that the practical maximum clothes loads to maintain the maximum efficiency can be predicted based on this critical probability p_c. This provides a qualitative interpretation of why the drying efficiency decreases beyond the threshold load based on the amount of the effective air path qualitatively.

V. CONCLUSION

We have shown the different response of the activity parameter by using the fabric characteristic parameter α and reproducing experimental data using the physics-based model. The proposed model was validated using two different fabric types with experimental data and also the results of Deans's literature [10]. Although our models have shown the right direction qualitatively, the effect of the clothes load could not be reproduced when the clothes load is too heavy or too light. Thus, we introduced the percolation theory to interpret qualitatively in the previous section. This validated physics-based model is now being used in our lab to optimize the drying process under various load conditions for a prespecified objective function.

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