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ABSTRACT

Clothes drying accounts for a significant amount of energy consumed in residential and commercial sectors. Thermal vacuum clothes drying technology (TVCD) is proposed as an advanced clothes dryer that can significantly reduce the energy requirements by expediting the drying process. In the conventional convective clothes dryer, hot dry air is introduced into the drum which gets in direct contact to dry the clothes. This process is energy inefficient since the significant amount of heat and the water carried out with the exhaust stream are wasted. In contrast to the conventional convective drying technique, the drying mechanism of TVCD is through nucleate boiling at low temperature due to reduced vessel pressure. The process is not only efficient but also reduces the required time for drying. This paper aims to develop a comprehensive thermodynamic model to predict the transient drying process of TVCD. The three-stage system-level model can simulate the water content variation in the textile under various operational conditions, with detailed analysis of individual components. The preliminary results show that the drying time of 3 lb textile from 70% to 2.5% in TVCD is approximately four times less than the time required in the conventional clothes dryer. Parametric studies help understanding the effect of operating conditions and component geometry on the system performance, and the system's energy consumption is also analyzed.

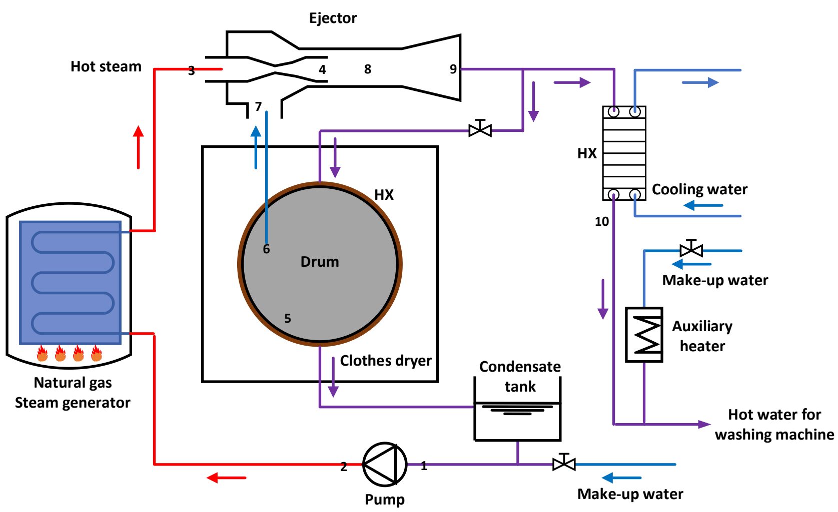
1. INTRODUCTION

Clothes drying is an energy-intensive processes in residential and commercial sectors, consuming approximately 657 TBtu (192.5 kWh) of energy annually in the US (EIA, Baseline Energy Calculator, 2020). The conventional clothes dryers generally use either electric resistance heaters or natural gas combustion to heat the air from ambient and then blow the hot dry air into the drum where the clothes are tumbling. The water in the wet fabric evaporates and then mixes with the dry air. The warm wet air leaves the drum and is often exhausted outside. This process requires a vent and is inefficient because large amount of heat and water are wasted with the exhaust stream. Additionally, this approach's drying mechanism mainly relies on the evaporation due to vapor pressure difference and thus is relatively slow. Thermal vacuum clothes drying technology (TVCD) is proposed as an advanced clothes dryer which can intensify the drying process. This new approach reduces the chamber pressure to activate the boiling mechanism for drying. It is efficient and faster than the conventional clothes drying process. In this paper, a physics-based model for predicting the transient vacuum drying process is developed. The model considers the transient state of each component of TVCD and can simulate the variation of water content within the fabric. The proposed model is employed to compare the drying behaviors between the TVCD and the traditional convective clothes dryer. The parametric studies for the TVCD including the effect of drum pressure, heat flux, and fabric material are also conducted.

2. SYSTEM DESCRIPTION

The thermal vacuum clothes drying system investigated in this study consists of a natural gas steam generator, ejector, drying chamber (drum), heat exchanger, and water pump. The schematic view and the p-h diagram are shown in Figure 1(a) and (b). This system's main idea is to use the hot steam passing through the ejector to generate low pressure for the drying chamber. A natural gas steam generator is utilized to convert the water to high-pressure steam, which will be directed to the ejector. When the hot steam enters the ejector's motive nozzle, low pressure is generated, which evacuates the air-water mixture from the drying chamber through the suction nozzle of the ejector. The fluids from the motive nozzle and the suction nozzle mixes in the mixing section. A portion of the warm steam from the ejector outlet is used as a heat source to heat the drum and clothes. After exchanging heat with the drum or clothes, the steam condenses to liquid water, and it is collected in a condensate tank. The condensed water in the tank is then pumped to the steam generator and starts a new cycle. The remaining warm steam at the ejector outlet is directed to a heat exchanger, in which the steam is recovered for the hot water usage in the washing machine.

(a)



(b)

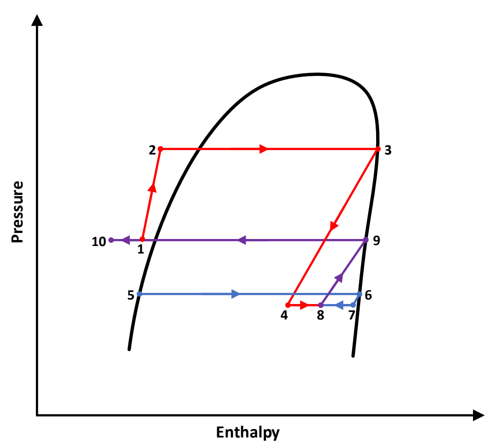


Figure 1: (a) Schematic and (b) p-h diagram of thermal vacuum clothes drying system

3. MATHEMATICAL MODEL

This section describes the numerical modeling procedure used to analyze the transient drying curve of the TVCD. Based on drying physics, there are two main mechanisms observed in the process: evaporation and boiling. When the TVCD starts operating, the chamber's air is extracted; thus, the pressure is reduced. Before the saturation temperature point has been reached, the water within the fabric vaporizes through evaporation. In order to simplify the model and make it solvable, the process is artificially separated into two stages. As shown in Figure 2, the first stage is the isothermal vacuum process, in which the pressure drops from the atmospheric pressure to the design pressure or target vacuum level. In the non-boiling regime stage, the temperature of water within the fabric keeps increasing until it hits the saturation point. Finally, the boiling is activated in the final stage (boiling regime). As a result, the three-stage system model is proposed to describe the drying process of TVCD. The thermodynamic state-point analysis incorporated with a one-dimensional ejector model is implemented to simulate the transient drying curve. It is solved iteratively with the computer program Engineering Equation Solver (EES) (Klein and Alvarado, 1992).

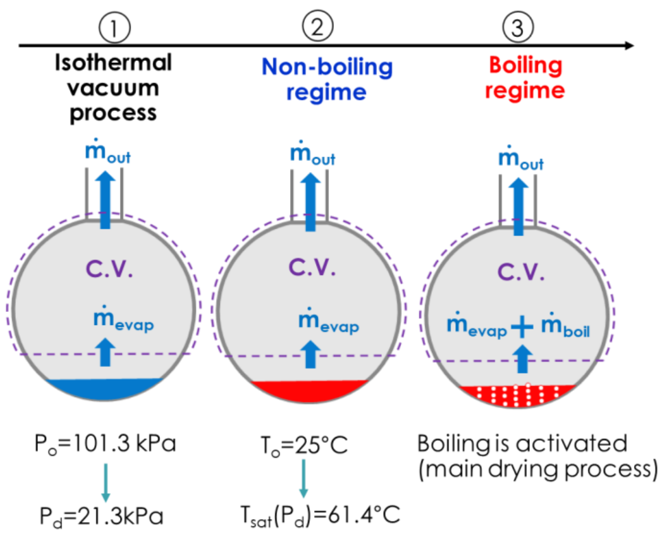


Figure 2: Three stages of vacuum drying process in the drum

3.1 Steam generator

The steam entering the motive nozzle of the ejector is generated by a natural gas steam generator. The useful heat supplied to the water can be expressed as the following equation.

$$\dot{Q}_{water} = \dot{m}_w \left(h_{b,out} - h_{b,in} \right) \tag{1}$$

where m_w is the mass flow rate of water entering the steam generator, and $h_{b,in}$ and $h_{b,out}$ are the enthalpy of the fluid at the steam generator's inlet and outlet. Note that the vapor quality and pressure at the outlet of steam generator are the design values, which are used for the calculation of the enthalpy. For a given steam generator efficiency, the fuel energy required to generate the steam is calculated by,

$$\dot{Q}_{fuel} = \frac{\dot{Q}_{water}}{AFUE} \tag{2}$$

where *AFUE* is the annual fuel utilization efficiency of steam generator.

3.2 Steam Ejector

The steam ejector in the system is simulated using the model developed by Kornhauser (1990), which is based on the method of constant pressure mixing. The rationale for using this model is to predict the outlet conditions (diffuser outlet state) and entrainment ratio with given inlet conditions (motive and suction inlet states) as well as the assumption of the isentropic efficiencies of the ejector motive nozzle, suction nozzle, and diffuser. The mass, momentum, and energy balances are conducted in sub-sections of the ejector.

In the motive nozzle, the outlet condition is estimated with the equation of state and energy balance.

$$h_{mn,out} = h_{mn,in} + \eta_{mn}\left(h_{mn,out,s} - h_{mn,in}\right) \tag{3}$$

where $h_{mn,out,s}$ is the enthalpy at the outlet of motive nozzle under isentropic process and η_{mn} is the isentropic efficiency of motive nozzle. $h_{mn,in}$ is the enthalpy at the inlet of motive nozzle, which is equal to that at the outlet of the steam generator.

The velocity of the fluid at the outlet of the motive nozzle is

$$V_{mn,out} = \sqrt{2\cdot\left(h_{mn,in}^2 - h_{mn,out}^2\right)} \tag{4}$$

In the suction nozzle, the outlet condition is estimated with the of state and energy balance equations.

$$h_{sn,out} = h_{sn,in} + \eta_{sn}\left(h_{sn,out,s} - h_{sn,in}\right) \tag{5}$$

where $h_{sn,out,s}$ is the enthalpy at the outlet of the suction nozzle under the isentropic process and η_{sn} is the isentropic efficiency of the suction nozzle. $h_{sn,in}$ is the enthalpy at the inlet of the suction nozzle, which is determined based on the enthalpy at the outlet of the vacuum chamber (drum).

The velocity at the outlet of the suction nozzle is

$$V_{sn,out} = \sqrt{2\cdot\left(h_{sn,in}^2 - h_{sn,out}^2\right)} \tag{6}$$

In the mixing section, the outlet condition is derived from the conservation of energy and momentum.

$$h_{diff,in} = r_m \cdot h_{mn,out} + \left(1 - r_m\right)\cdot h_{sn,out} \tag{7}$$

where r_m is the ratio of motive to total mass flow rate.

$$r_m = \frac{\dot{m}_{mn}}{\dot{m}_{mn} + \dot{m}_{sn}} \tag{8}$$

$\dot{m}_{mn}$ and $\dot{m}_{sn}$ are the mass flow rates of the motive nozzle and suction nozzle, respectively.

The velocity at the inlet of the diffuser is estimated with the following equation.

$$V_{diff,in} = r_m \cdot V_{mn,out} + \left(1 - r_m\right)\cdot V_{sn,out} \tag{9}$$

The pressure in the mixing section is assumed by a specified pressure drop across the suction nozzle, which corresponded to a 1K drop in saturation temperature. This assumption was made based on the experimental observation of Elbel (2011) and Harrell and Kornhauser (1995).

In the diffuser, the enthalpy of the fluid at the outlet is estimated with the conservation of energy and equation of state.

$$h_{diff,out,s} = h_{diff,in} + \left(\frac{V_{diff,in}^2}{2}\right) \tag{10}$$

$$h_{diff,out} = h_{diff,in} + \eta_{diff}\left(h_{diff,out,s} - h_{diff,in}\right) \tag{11}$$

where $h_{diff,out,s}$ is the enthalpy at the diffuser outlet under isentropic process, and η_{diff} is the diffuser's isentropic efficiency. The pressure at the diffuser outlet is a function of $h_{diff,out,s}$ and $s_{diff,in}$ (the entropy at the inlet of diffuser), and it is slightly higher than the atmospheric pressure, which is assumed to be 102 kPa in the current model.

3.3 Vacuum Drying Process in Drum

The transient water content in the fabric during the vacuum drying process in the drum is simulated with a three-stage model. Here, a non-dimensional parameter of water content in the fabric is defined as follows,

$$X \equiv \frac{w}{M_{t,dry}} \tag{12}$$

where w is the mass of the water content in the clothes and $M_{t,dry}$ is the mass of the dry textile.

3.3.1 Isothermal vacuum process

During the first stage of the vacuum drying process, the drum pressure decreases from the atmosphere to a target vacuum level. The primary mechanism of the drying at this stage is based on evaporation. Refer to the schematic of stage 1 in Figure 2, the mass balance in the control volume can be written as

$$V\frac{d\rho(t)}{dt}+\dot{m}_{out}-\dot{m}_{evap}=0 \qquad (13)$$

V is the drum's volume, ρ is density of air water mixture in the drum, $\dot{m}_{out}$ is the mass flow rate ejecting from the drum and $\dot{m}_{evap}$ is the evaporation rate of the water. The mass flow rate at the drum outlet is determined by the entrainment ratio of the steam ejector.
The drum pressure is the summation of the partial pressures of air and water vapor, and the density of each is obtained through the mass balance in the control volume.

$$P=\rho_a(t)R_aT+\rho_w(t)R_wT \qquad (14)$$

where ρ_a is the density of air, R_a is the gas constant for dry air, *T* is absolute temperature of the gas in the chamber, ρ_w is the density of the water vapor, and R_w is the gas constant for water vapor.
The evaporation rate is assumed to be constant and estimated by the mass flow rate of the outlet flow at the end of this stage. The rate of change of water removed from the clothes is expressed by the following equation.

$$-\frac{dX}{dt}=\frac{\dot{m}_{evap}}{M_{t,dry}} \qquad (15)$$

3.3.2 Non-boiling regime
At stage 2 of the vacuum clothes drying process, the water within the clothes is heated up but still under the boiling point of the related pressure. The principal drying mechanism is via evaporation at the liquid vapor interface, and the drying curve during this stage is estimated with the same equation (Eq. 15) in the stage 1. The duration of stage 2 is determined through the required energy for the water remained in the fabric to reach the boiling temperature under the certain drum pressure. The boiling is assumed to happen when the accumulated energy transferred to the water equals to required sensible heat transfer.

$$M_{liquid}C_{p,l}\left(T_{sat}-T_o\right)=\sum\eta_a\dot{Q}_{steam}\Delta t \qquad (16)$$

where M_{liquid} is the liquid water remained in the fabric at the beginning of the stage 2, and η_a is the effective contact ratio for sensible heat transfer.

3.3.3 Boiling regime
When the boiling point is reached, the water escapes from the fabric rapidly and it is the main drying process for vacuum clothes dryer. The liquid water becomes vapor not only via evaporation but also through boiling process when contact the solid surface. The rate of change of water removed from the clothes during this stage is expressed by the summation of evaporation rate and boiling rate.

$$-\frac{dX}{dt}=\frac{1}{M_{t,dry}}\left(\dot{m}_{evap}+\dot{m}_{boiling}\right) \qquad (17)$$

The boiling rate depends on the heat transfer to liquid water within the fabric, which can be expressed as follows,

$$\dot{m}_{boiling}=\frac{\dot{Q}_{nucleateboiling}}{h_{fg}}=\frac{\dot{Q}_{steam}\cdot a(X)}{h_{fg}} \qquad (18)$$

where $Q_{nucleateboiling}$ is the heat transfer rate of nucleate boiling and h_{fg} is the latent heat of vaporization. Q_{steam} is estimated from the enthalpy difference between inlet and outlet of the heat exchanger. The water activity coefficient, *a(X)*, is a function of moisture content of the medium and is suggested by Lambert *et al.* (1991) to represent the material effect. Besides, the sorption-isotherms from the work of Krischer and Kast (1978) are used to determine the water activity coefficient and approximated with the following equation form proposed by Lambert *et al.* (1991).

$$a(X)=1-\frac{\beta\cdot X+\delta}{1+2^{(\gamma\cdot X)}} \qquad (19)$$

The isotherms parameters for typical fabrics such as cotton, wool, and nylon are summarized in the work of Deans (2011), as presented in Table 1. The non-linear ordinary differential equation (Eq. (17)) is solved with Runge-kutta method.

Table 1: Parameters of the isotherms for typical fabrics (Deans, 2011)

Material	Parameters of isotherms
Cotton fabric	β=18, γ=30, δ=2
Wool and highly porous fabrics	β=6, γ=18, δ=2
Nylon and synthetic fabrics	β=25, γ=65, δ=2

4. ENERGY ANALYSIS OF VACUUM CLOTHES DRYING SYSTEM

The clothes dryer's performance index used here is the Combined Energy Factor (*CEF*), which is a measure of energy efficiency following the test procedure employed by the United States Department of Energy (DOE), as specified in 10 CFR 430 (2013). The higher a dryer's CEF value, the more energy efficient a dryer will be. The *CEF* is calculated from

$$CEF = \frac{M_{bonedry}}{E_{cc}} \tag{20}$$

where $M_{bonedry}$ is the bone-dry test load weight in lb and E_{cc} is the total energy consumption per dryer cycle in kWh.
The total energy consumption per dryer cycle is calculated by the summation of gas energy consumption, electrical energy consumption of gas dryer and the standby/off mode energy consumption.

$$E_{cc} = E_{gg} + E_{ge} + E_{TSO} \tag{21}$$

Here, E_{gg} is the fuel energy consumption of the vacuum device in kWh per cycle (of drying), E_{ge} is the total energy consumption of the electrical equipment, i.e., water pump in kWh per cycle, and E_{TSO} is the per-cycle standby mode and off mode energy consumption in kWh.
The gas energy consumption is estimated by the required fuel energy for the steam generator from Eq. (2) drying the drying cycle.

$$E_{gg} = \int_{t=0}^{t=t_{cycle}} \dot{Q}_{fuel} dt \tag{22}$$

The electrical energy consumption is found from the power requirement of the water pump and it is calculated by

$$E_{ge} = \int_{t=0}^{t=t_{cycle}} \left(\frac{S_w \left(P_{pump,o} - P_o \right)}{\eta_p} \right) dt \tag{23}$$

where S_w is the volume flow rate of water, $P_{pump,o}$ is the pressure at the outlet of pump, P_o is the pressure in atmosphere, and η_p is pump efficiency.
The per-cycle energy consumption of standby mode and off mode is estimated with the following equation.

$$E_{TSO} = (8760 - 283 \times (t_{cycle} / 3600) \times 2 \times 10^{-3}) / 283 \tag{24}$$

where 8760 is the total hour of a year and 283 is representative average number of clothes dryer cycles in a year. t_{cycle} is the total drying time per cycle for the clothes from 57.5% to 2%, and the standby power is assumed to be 2W suggested in the work of Meyers et al. (2010).
One of the advantages of this novel drying system is that some of the warm steam could be recovered and used as a hot water source for the washing machine. E_{rec} is the total energy recovered for hot water usage during the drying process, which is calculated by the following equation.

$$E_{rec} = \int_{t=0}^{t=t_{cycle}} \left(\dot{m}_r \left(h_{diff,out} - h_o \right) \right) dt \tag{25}$$

where $\dot{m}_r$ is the mass flow rate of steam passing through the heat recovery device, $h_{diff,out}$ is the enthalpy at the outlet of ejector, and h_o is the enthalpy of water at atmosphere. Note that the at the stage 1 of drying process, the valve between ejector outlet and drum heat exchanger is fully closed (refer to Figure 2), and all the warm steam is directed for heat recovery. At the stage 2 and stage 3, this valve is fully open, and the mass flow of steam in the recovery device equals to the mass flow rate at the inlet of suction nozzle of the ejector based on the mass balance.

5. RESULTS AND DISCUSSION

5.1 Simulation drying cure of TVCD

The simulation follows the standard procedure from the US DOE D2 test procedure outlined in 10 CFR 430 (2013). The weight of bone-dry test load for the simulation is 3.832 kg (8.45 lb). The initial and final moisture contents for the drying process are set as 57.5% and 2%, respectively. An example is shown in Figure 3 to demonstrate the simulation results of the drying curve and pressure curve predicted by the proposed model. The conditions used in the simulation are summarized in Table 2. Figure 3(a) presents the predicted drying curve of the TVCD. There are two distinct regions during the vacuum drying process. In the first region, the drying mechanism is evaporation, and the drying rate (the slope of the drying curve) is slower the second region. In the second region, the boiling mechanism dominates. The drying rate is faster, but it decays when the water content ratio for the clothes is lower than a certain value. Figure 3(b) shows the predicted pressure curve of the TVCD. The pressure of the chamber is first reduced from atmospheric pressure to the target pressure, which is 21.3 kPa in the current example. As the boiling occurs, a large amount of water vapor is generated and further increases the system pressure. Then, the pressure decreases when the drying rate decays.

(a) (b)

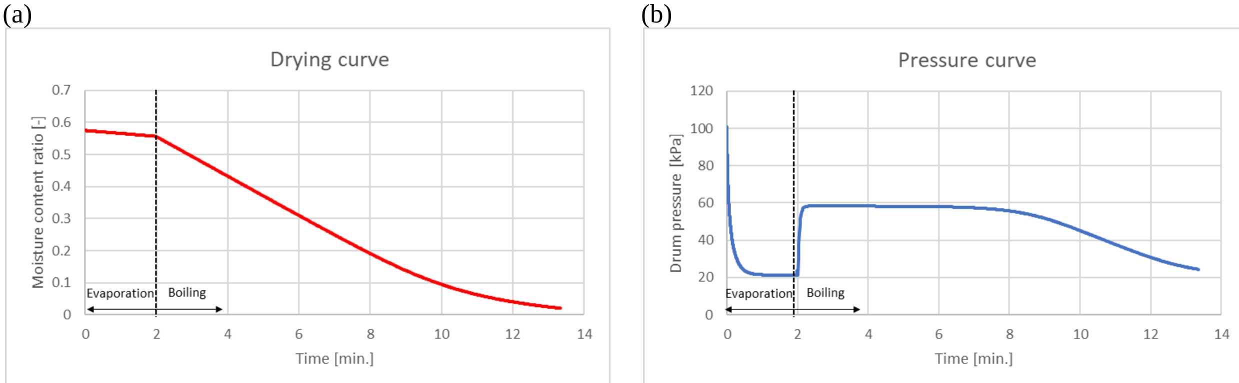


Figure 3: (a) Drying curve of the test fabric and (b) drum pressure curve for the vacuum drying process.

Table 2: Conditions used in the demonstrative example

Geometry of drum	D=0.4572 m, L=0.3048 m
Material and bone-dry mass of the textile	Cotton, M_d=3.832 kg=8.45 lb
Initial and final moisture contents	X_i=57.5%, X_f=2%
Parameters of the sorption isotherm	β=18, γ=30, δ=2
Effective area ratio	η_a=0.5
Initial conditions of the air inside the chamber	P_o=101.3 kPa, T_o=25°C, RH=50%
Steam generator	P_{in}=792.89 kPa, m_w = 7 g/s, x_{out}=1, $AFUE$=0.95
Ejector	η_{mn}=0.7, η_{sn}=0.7, η_{diff} =0.7
Pump	η_p=0.8

5.2 Comparison of vacuum drying and convective clothes drying

The proposed model is also used to compare the performance of thermal vacuum drying and convective drying. The experimental drying curve of a household compact tumble clothes dryer reported by Yadav and Moon (2008) is used as the baseline. The clothes dryer in their experimental work was a conventional electric vented-type unit with 2 kW power requirement. The rated capacity of the dryer was 4.5 kg, and the drum volume was 125 L. The experiment was conducted following the conditions specified in ANSI standard (1992). The bone-dry mass was 1.36 kg (3 lb), and the initial and the final moisture contents were 70±3.5% and 2.5-5%, respectively. The ambient temperature and humidity were 24±2°C and 50±10%, respectively. In the simulation, the diameter and the length of the drum were set as 53.3 cm and 56 cm to match the volume of the drum (i.e., 125 L) tested in Yadav and Moon's work. The bone-dry mass was 1.36 kg (3 lb), and the initial and the final moisture contents were set as 70% and 2.5%, respectively. The target system pressure was set as 40 kPa, and the mass flow rate of steam was 3 g/s. The other parameters used in the simulation were same as those listed in Table 2.

The drying curves for the clothes under thermal vacuum drying and convective drying are presented in Figure 4. The blue symbols represent the experimental results of convective drying from Yadav and Moon (2008) work and the red solid line is the simulation results of the TVCD. As seen, the time required for the TVCD to reduce the moisture content from 70% to 2.5% was within 12 min, which means the vacuum drying is around four times faster than the conventional convective drying. The total energy consumption for the electric clothes dryer (convective drying) measured by Yadava and Moon is 1.206 kWh. The predicted energy consumption of the TVCD under the conditions mentioned above is 1.54 kWh, including the gas energy consumption, electrical energy consumption of gas dryer, and the standby/off mode energy consumption. However, 1.104 kWh of the energy in the TVCD could be recovered from high-temperature steam for usage in washing machine. In other words, the actual energy required for the drying process is only 0.436 kWh. As a result, the thermal vacuum drying techniques can save drying time and energy if the steam is recovered properly. In addition, the system performance of the TVCD can be improved by optimizing the components or operating conditions such as drum pressure and steam flow rate.

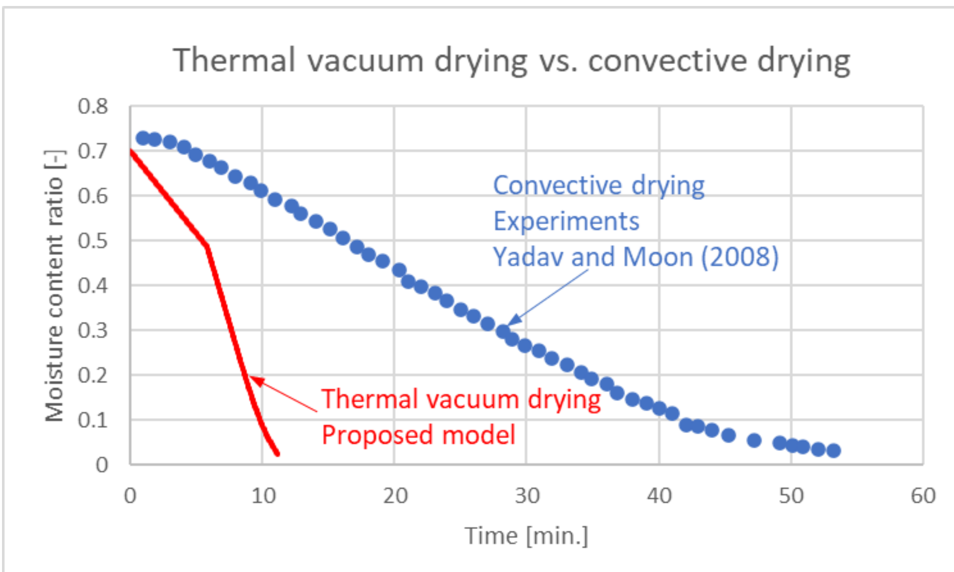


Figure 4: Comparison of thermal vacuum drying and convective drying

5.3 Effect of drum pressure

The saturation temperature and the latent heat of vaporization are two important parameters in the vacuum drying process. As mentioned above, the TVCD is more efficient than the convective clothes dryer due to its boiling mechanism. For a certain vacuum pressure, the water temperature or the fabric temperature needs to be higher than its related saturation temperature to activate the boiling. The required energy for the phase change process is related to the latent heat of vaporization. Figure 5(a) shows the dependences of saturation temperature and latent heat of vaporization of water on pressure. In general, the T_{sat} decreases as the system pressure decreases, and the h_{fg} increases as the system pressure decreases. The effects of pressure on the predicted drying time and *CEF* are presented in Figure 5(b). The simulation of the drying process was conducted with the same inputs but varying the pressure conditions. Note that the high-temperature steam used in the facility is assumed to provide sufficient heat flux and activate the boiling mechanism. The simulation results show that the *CEF* increases as the rise of the pressure. A higher system pressure means less energy is needed for vacuuming the chamber or lowering the system pressure from the atmospheric condition. The latent heat of vaporization is lower at a high-pressure condition, indicating less energy is required for the phase change process. Moreover, the drying cycle is shorter at a higher pressure. Assuming the boiling point has been reached, the fabric has a higher temperature and thus higher energy of molecular motion. This provides more chance to break the intermolecular bonds holding the water molecules together and evaporates the water. However, the clothes may be damaged when the temperature increases to a certain point, depending on the fabric type.

(a) (b)

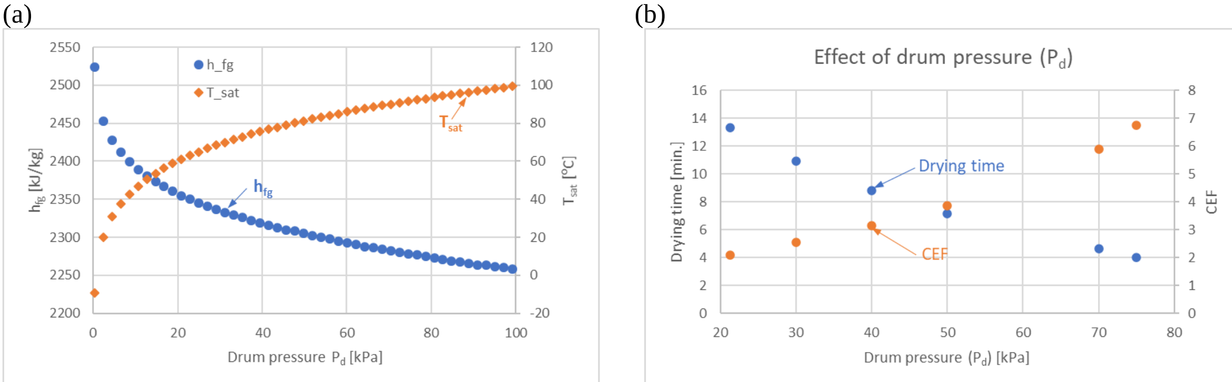


Figure 5: (a)Saturation curves of water, and (b)Effect of drum pressure on the predicted drying time and CEF

5.4 Effect of fabric material

Fabrics are in general porous materials with complex structure, and they are classified as the hygroscopic and non-hygroscopic according to the ability to absorb moisture from the environment. The hygroscopic material is one that actively attracts or adsorb water from its surroundings without bounding, which can be removed by drying. The non-hygroscopic material, in contrast, does not readily take up and retain moisture. This characteristic affects the sorption capacity and further drying behavior. Figure 6 shows the predicted drying curves of cotton fabric, nylon and synthetic fabrics, and wool and highly porous fabrics under thermal vacuum conditions. As can be observed, nylon and synthetic fabrics have the higher drying rate, followed by cotton fabric, and then wool and highly porous fabrics. This variation in drying rate can be explained with the hygroscopicity of the materials. As the water molecule has more chance to leave the fabric and touch the internal drum surface with high temperature, it is easier to evaporate or boil.

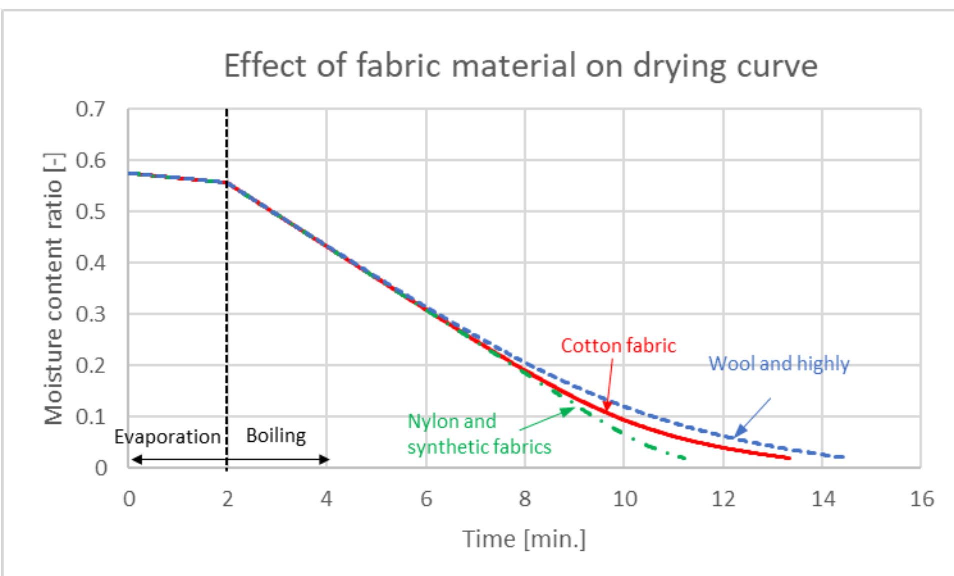


Figure 6: Effect of fabric material on dryinig curve

6. CONCLUSIONS

In this paper, a theoretical model has been developed to simulate the transient drying process of thermal vacuum clothes dryer. The simulation results of the TVCD were compared to the experimental results of the convective clothes dryer in the literature. Parametric studies were also conducted to understand the effect of operation conditions on drying time and energy consumption of the TVCD. The key findings from the present study are as follows.

- The thermal vacuum clothes dryer is an advanced clothes dryer that is faster and energy-efficient. Compared to the convective clothes dryer, the TVCD takes around one-fourth of the time to dry the 3 lb textile from 70% to 2.5%.
- The simulation results show that the *CEF* of TVCD increases and the drying time decreases as the drum pressure becomes higher. Nevertheless, the higher the drum pressure, the higher the saturation temperature (boiling point). The clothes may be damaged when the temperature increases to a certain level.
- The model adequately describes the effect of the fabric type on the drying behavior. This may help optimizing the operating conditions of the TVCD.
- The prototype of TVCD will be developed, and the proposed model will be validated with the corresponding experiments.

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