14th IEA Heat Pump Conference
15-18 May 2023, Chicago, Illinois

The Dynamic behaviors on Drying Performance of Heat Pump Dryer using a Reduced Order Model

Yoonjei Hwang*, Jinwook Lee, Wansoo Kim, Kangwook Lee, Yeonha Seong,
Mansu Park and Saikee Oh

H&A R&D Center, LG Electronics Inc., 08592 Seoul, Korea

Abstract

Dynamic behaviors be observed on a heat pump dryer to maximize drying performance under various condition through the change of compressor frequency. In order to optimize the drying performance, it is necessary to predict the dynamic behavior of air side and refrigerant side together. However, as the refrigeration cycle is optimized by a constant state condition of air at the design stage, it has less chance to implement design parameters to air flow path. In the study, simulation has been done to refrigerant and air side simultaneously under a concept of model based environment. There was no issues for integrated model because the geometrical model(3D) for air side converted to a reduced order model to make shorten the simulation time. The model for heat exchangers took a finite volume method that calculates the governing equations for several segments. The compressor model came from the analytical models for gas compression in control volumes. For the model for drum, it was predicted through the artificial neural network(ANN) learned by the test data set from experimental set up. In order to verify the system model that integrates the refrigeration and air cycle including drum model in the Dymola® environment, the dynamic characteristics data of the dryer for 2 ~ 8 kg drying load conditions were acquired. The result of numerical study shows reasonably low errors when compared with the experimental data. The pressure of refrigeration cycle and drying time at the drying section showed an error of 10% or less.

Keywords: Heat pump dryer, Model-based design, Reduced order model, ANN(Artificial Neural Network);

---

1. Introduction

A dryer for clothes be divided into a direct heating using an electric heater and a heating by heat pump using a refrigerant cycle according to a heating method. The heat pump-based clothes dryer is more energy efficient than the electric heater-based because it reuses waste heat to remove moisture from the clothes inside the drum.[1] The heat pump clothes dryer is a closed-loop system where the air passed through drum be cooled to low temperature at the evaporator and re-heated it to high-temperature air through the condenser. The design of the closed loop dryer is more difficult than the direct exhaust dryer, in which the air absorbed a moisture from the clothes in the drum is directly discharged out of the dryer. A Chailoet et al. investigated the effects of key parameters through experiments on the energy efficiency of the clothes dryer[2] and Xiang Cao et al developed a quasi-steady-state simulation of the heat pump clothes dryer to optimize the design parameter.[3]

The transient behavior, in which the state of air and refrigerant is changed continuously from the start of product operation to the end, be observed at the heat pump-based clothes dryer. Therefore, considering the change of air state according to the evaporation amount of moisture in the clothes inside the drum is important to predict the drying performance. A bunch of tests are repeated to optimize parameters of performance during the design stage of the dryer because the range of operation modes is wide depending on the purpose of

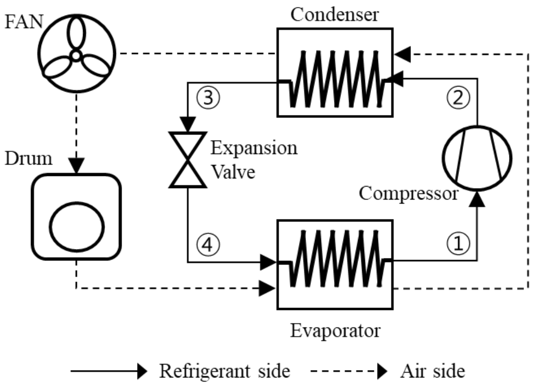
---

* Corresponding author. Tel.: +82-10-2343-3830
*E-mail address:*yj.hwang@lge.com.

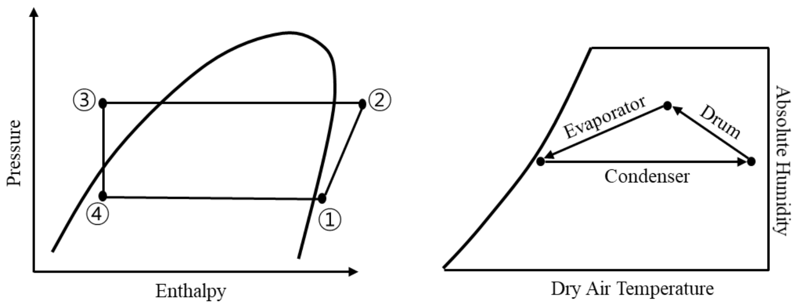
customer needs. As a result, it causes low product competitiveness and high cost of product development. The analytical model for simulation is need to solve these issues and predict the physical phenomenon at the transient state in the drying process. During the design process of the product, the main components of refrigerant cycle are designed to achieve maximum drying performance after deciding the geometrical parameters of the circulated air flow path to minimize flow resistance through three-dimensional CFD model. In general, the simultaneous simulation in a same environment is limited since each simulation is highly dependent on their own simulation environment. Therefore, optimization must be required at the system level, and a model-based simulation environment makes it happen. The overall system divides into sub-component models based on functional classification and it provides convenient environment where the entire system can be evaluated through only modification and validation for sub-components even if there has a needs to design modification. The mass flow rate of the circulated air at the flow path in the dryer is calculated using a reduced-order model in the model-based environment for simultaneous analysis. The reduced-order model could be a surrogate model, in which the complexity of numerical simulation is simplified even there has a loss of fidelity, it provides shorten analyzing time to the airflow path resistance according to various geometrical parameters. In the study, a dynamic simulation for clothes dryer of a closed-loop using R134a refrigerant as a working fluid was developed to evaluate drying performance and optimize design parameters. The Modelica language in the Dymola be used for system modeling of the heat pump-based dryer. The developed system model was verified through comparison with experiments by loads of clothes and operating conditions.

2. System Overview

The schematic of the heat pump dryer cycle and the change of thermodynamic properties according to the air and refrigerant side conditions are shown in Fig.1. The refrigerant of low-temperature and low-pressure is flowed into a compressor and compressed to the high-temperature and the high-pressure as a vapor state, and phase changes to liquid state through heat exchange with airside. Refrigerant after the expansion valve flows into the evaporator in a low-temperature and low-pressure state, the phase changes to the vapor state through heat exchange with high-humidity air, and the air flows into the drum again through the condenser.



(a) Schematic diagram of the heat pump dryer



(b) P-h diagram of refrigeration side (c) Psychrometric chart of air side

Fig. 1. Schematic diagram of the heat pump-based dryer

The dynamic model for dryer have to respond to the changes by control logic for individual optimization as well as respond to wide variety of operating modes depending on the user's requirements. A model considering various physics was implemented to simulate the dynamic characteristics of each component caused by the real-time change of the operating frequency of the compressor, the rotation speed of the fan and drum, and the opening of the electronic expansion valve.

3. Modeling Approach

3.1. Modeling for Refrigerant cycle

The dynamic model developed in the study was created using the Modelica language in the Dymola environment utilizing TIL suite (2022) by TLK Energy. The version of TIL used in the study is 3.10.0. The rotary compressor model was defined as the mass flow rate and power consumption according to condensing and evaporating temperature calculated from both the displacement and frequency as shown in equation from (1) to (3). Each of efficiency was defined using the performance data of the compressor by LGE. The mass flow rate of the refrigerant is calculated from the volumetric efficiency, and the compressor outlet enthalpy can be predicted from the isentropic efficiency. Therefore the power consumption of the compressor can be predicted as well.

$$\eta_{vol} = \frac{\dot{m}_{ref}}{\rho_{ref,s} \cdot rps \cdot \mathrm{V}_{dis}} \tag{1}$$

$$\eta_{isen} = \frac{h_{dis,isen} - h_{suc}}{h_{dis} - h_{suc}} \tag{2}$$

$$\eta_{eff,isen} = \frac{\dot{m}_{ref}(h_{discharge,isen} - h_{suction})}{P_{shaft}} \tag{3}$$

In the case of model for the electronic expansion valve, an empirical correlation was proposed using not only the diameter, but also length of the orifice as the geometrical parameter because the characteristics of mass flow rate to an electronic expansion valve are depended on the pressure drop of the refrigerant in orifice.[4] As the coefficient of flow rate is the shape coefficient of the orifice, the variable coefficient was developed based on the experimental data reflecting the component characteristics, because the characteristics are normally different depends on manufacturers even if the diameter is the same.

$$\dot{m}_{eev} = C_D A\sqrt{2\rho_{in}(P_{in} - P_{out})} \tag{4}$$

Both the condenser and evaporators are fin-and-tube type heat exchangers. Heat and mass transfer in the heat exchanger occurs relatively slow compared to the compressor or the expansion device, however the boundary conditions keep on changed continuously. The change of state properties were calculated through a differential equation including a time derivative by a finite volume method, it calculates a tube through which refrigerant flows by dividing it into multiple control volumes. The heat exchanger model provided by TIL can be divided into a moist air cell and a tube wall cell for airside analysis, as well as VLE Fluid cell for refrigerant side analysis. All cells reflected a geometric information for fin and tube such as number of row, columns, fin pitch, and thickness. Each cell also contains the equations of mass, energy, and momentum balance for the analysis of unsteady states.

3.2. Modeling for Airflow loop cycle

The model for circulated rate of air flow in dryer was developed through the law of similarity based on the data measured from the fan test. After taking P-Q curve for fan by fan test, the pressure losses for each component must be predicted to take a system resistance curve. Eventually, the mass flow rate of air is calculated at the point where curves the system resistance and the pressure loss intersect. Simulation by three-dimensional CFD model for a complex shape of airflow path must be carried out so that detailed dimensions of components be considered, moreover simultaneous simulation with the refrigerant cycle system should be performed. There have limitations when trying to perform simultaneous analysis, it is limited due to the simulation speed difference between the refrigerant cycle and the three-dimensional CFD for airflow path. The reduced-order model for air flow rate can be a solution to synchronizing time difference. The response surface models for components were prepared based on simulation data for the airflow path to make the reduced-order model. The main advantage of doing that, it doesn't need to re-simulate performance for the entire area when a new event occurred like partial change of configuration, but only calculate performance using the configured reduced model maintaining fidelity.

The schematic of the cycle of the airflow path is shown in Figure 2. The airflow rate by fan is flowed into the drum inlet after pass through a porous plate and the rear duct sequentially. The air passed through the drum circulates continuously, to the front duct and through two mid ducts between the evaporator and the condenser. The model for air circulation flow was divided into four parts, which are front duct, mid duct (a), mid duct (b) and rear duct respectively, also the factors affecting flow path resistance were defined as input parameters when designing each component. For four sorts of duct, DOE based parameter optimization was conducted by 14 factors, which consist of the shape parameters selected and operating conditions. And then data from flow path analysis were collected through the simulation of the three-dimensional CFD. After, a total of 560 data were generated by this way, the reduced-order models for each duct were developed based on this data.

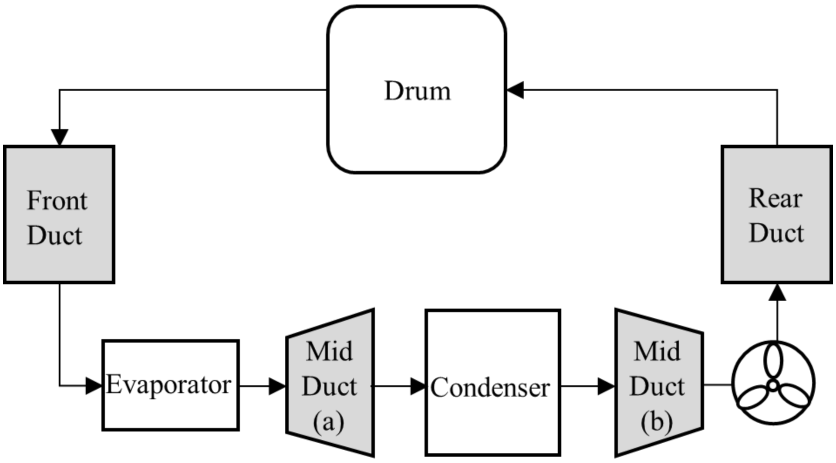


Fig. 2. Schematic of the circulated airflow path in a closed loop system

The heat exchanger model is defined by seven factors, which can be a tube diameter and relative humidity as an example, and by flow velocity that affect pressure loss. Coil Designer, a heat exchanger design tool, was used to find the data for pressure difference according to the pre-defined factors. During the process, the equation of correlation for pressure difference that be selected as an input to the coil designer, takes the equation developed by LGE. The result of process provides 80,000 simulation data.[5][6] The model for pressure loss in heat exchanger comes the result of learning process from ANN(Artificial Neural Network) based on the collected pressure loss data. For the model of Drum, 32-course data based on the drying loads from 1 to 20 kg, and pre-set drying mode like a Speed, Eco and Auto were collected. To make an ANN model, define first to main influencing factors such as drying load, drying status, moisture content, air temperature and humidity as an input parameter. When comparing the predicted value with the data which is not used for model learning, it was confirmed that there was no overestimation issues because it observed within 5% of the average error of cross-validation. The airflow rate of the system can be predicted by comparing the pressure at various operating conditions of the blowing fan with each of pressure drop model for components. It will be combined with the refrigerant cycle model in Dymola platform for simultaneous simulation. The concept of airside model has shown in Figure 3. When predict a value by implemented model, which is combined air flow and refrigeration cycle, compared with test data, it was confirmed that the accuracy was 97% as shown in Figure 4.

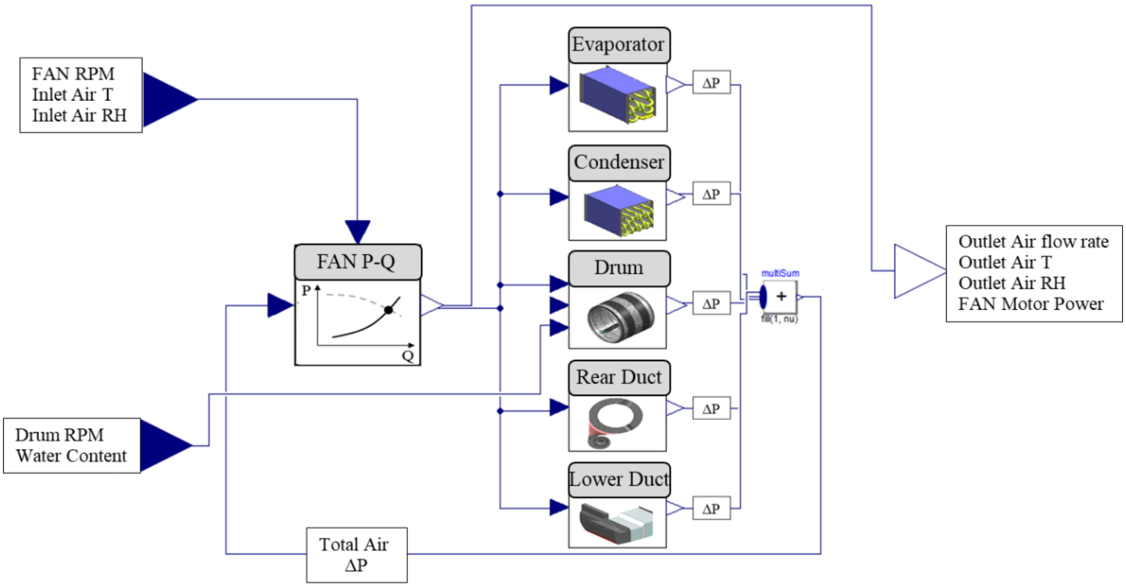


Fig. 3. The concept of the model for air flow rate in Dymola®

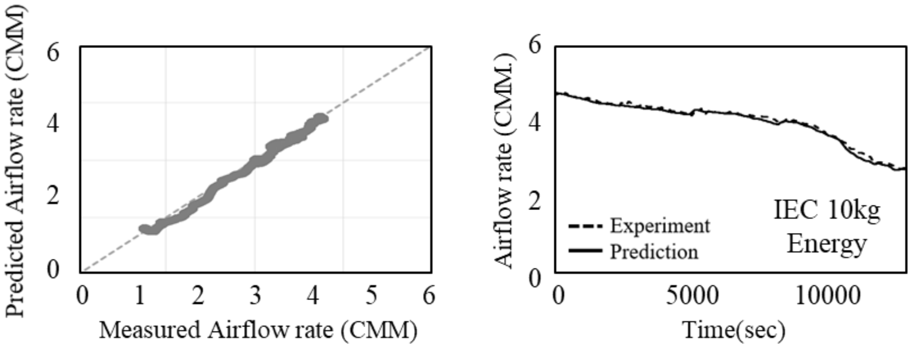


Fig.4 Comparison between measured and predicted air flow rate

3.3. Modeling for Drum

The rate of moisture extraction from clothes, where occurred inside of drum during the process of drying, be affected by the surface area of clothes when it contact with air flow. Therefore, the behavior of the clothes that changes as the drum rotates must be predicted by simulation model. However, there have many difficulties in numerically analyze physical phenomena because there happens heat transfer between air and cloth each other, together with heat exchange occurs between drum and the outside air at the same time. In the study, the data through experiments for the moisture extraction in drums is collected, and the model was developed by techniques for machine learning from based on the data. As shown in Figure 5, the experimental apparatus excluded the influence of the refrigerant cycle to measure only the change of air properties in the drum, and there have a device to make a constant temperature and humidity at inlet through a separate ducting system. The experiment was conducted for various operation modes until the initial moisture content of the clothes reached 0% from start at 60% based on the load commercially used, as shown in Table 1. The type of clothes follows the IEC 61121(International Electrotechnical Commission) standard and consists of Sheet, Pillowcase, Towel combinations. The measuring of a moisture content takes the signal from an electrode sensor of the dryer. ANN technique be introduced for modeling of the drum, the structure of input layer for ANN consists of three factors related to air characteristics (dry bulb temperature, absolute humidity, mass flow rate) and two factors related to clothes (amount of moisture, mass of clothes). Moreover, it has 3 hidden layers consist of 12 nodes per layer to calculate the sensible heat and the rate of moisture extraction between clothes in the drum as a output layer.[6]

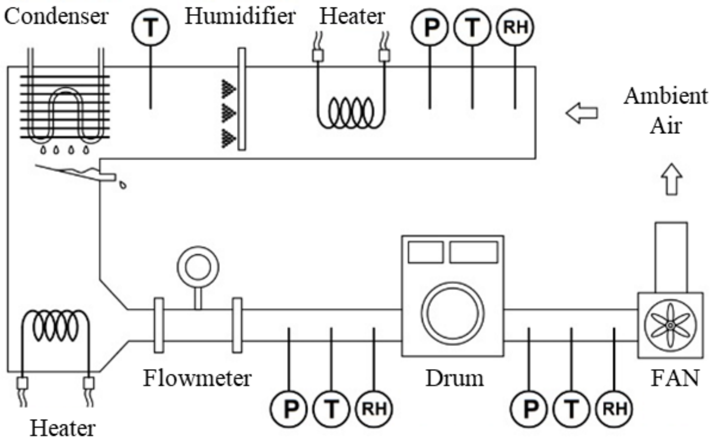


Fig. 5. Experimental equipment for acquiring learning data for drum

Pre-processing on the learning data has done to improve the performance of the drum model. During the experiment on drying, there has a tendency to sampled more data under high load conditions compared to low load conditions, and it caused a poor prediction performance to low load conditions. To solve it, not only additional sampling process has done to make a data samples as an even to the load conditions but also data samples, based on moving average line at 200-second, removed to avoid a noise caused by the measuring error from both to humidity sensor and the airflow meter. Figure 6 shows the results of comparing the model with the experimental data at the condition of 10kg and 20kg load. The prediction value for both to the sensible heat and the moisture extraction showed an 8% error if it compared with the experiment data based on movement average besides shown 13% error if it compared with the experiment data including noise.

Table 1. Test condition for drum

Parameter	Range
Clothes Load (kg)	10, 20
Circulated Airflow Rate (CMM)	3.0, 5.0
Drum Inlet Temperature (℃)	20, 40, 60, 80
Absolute Humidity (kg/kgDA)	0.01, 0.03, 0.05, 0.08

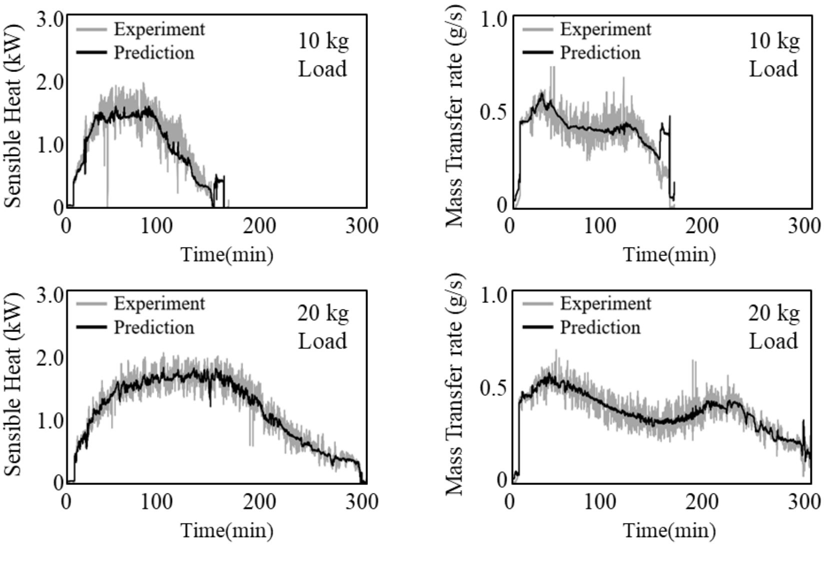
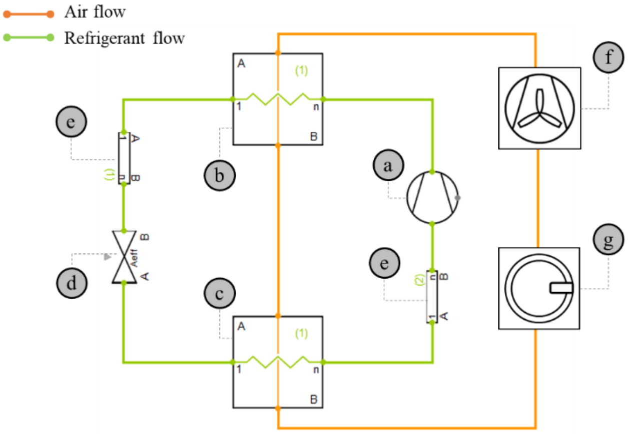


Fig. 6 Verification of drum ANN model

3.4. The system modeling for co-simulation

The study implemented the dynamic model that enables simulation together with refrigerant-side and air-side as combined systems that affect drying performance. For air flow path, the three-dimensional model be made first, and then it combined with refrigerant cycle model for co-simulation after three-dimensional model converted to 1D model through reduced order technique. The reason why it simulated as a three-dimensional CFD first is that the dimension of structure becomes dominant factor to determine accurate airflow rate, which should be affect to the drying performance in the dryer system, moreover, it could be a reliability issue if the structure model not be handled leakage properly. The 1D model for air-side validated before combining with refrigerant-side model to see how stably data transferred during order change from 3D to 1D. As a next step, the combined 1D system model synchronized again with real time control logic at every time intervals after combining two cycles. System simulation in a model-based environment was run through Dymola as a platform software. Figure 7 is a schematic diagram of the simultaneous simulation of refrigerant cycle and airflow cycle in the heat pump dryer system. The input and output values of the model to the main components of refrigerant cycle be defined as temperature, pressure, and flow rate of the refrigerant. The model for airflow rate calculates the airflow rate during circulation of air from the performance curve of the FAN and the total resistance by the system. Total resistance from the reduced order model of the ducting system that considered the shape of airflow path structures, included the heat exchangers and drum. The air properties during circulation is defined through the models both to heat exchangers and drum.

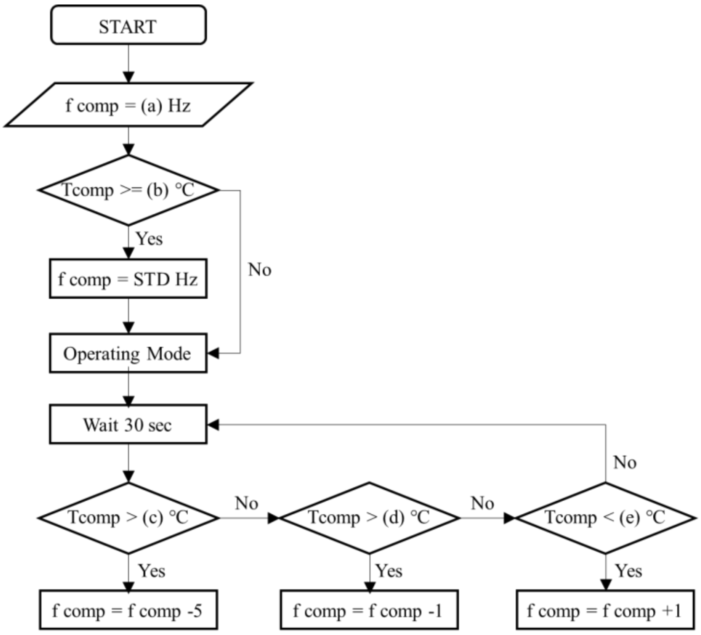


	Model	Input Parameter	Output Parameter
a	Compressor	Ref. P, h Operating Hz	Ref. P, h, $\dot{m}$
b	Condenser	Ref. P, h, $\dot{m}$ Air P, T, RH, $\dot{m}$	Ref. P, h, $\dot{m}$ Air P, T, RH, $\dot{m}$
c	Evaporator	Ref. P, h, $\dot{m}$ Air P, T, RH, $\dot{m}$	Ref. P, h, $\dot{m}$ Air P, T, RH, $\dot{m}$
d	Expansion Valve	Ref. P, h Operating Pulse	Ref. P, h, $\dot{m}$
e	Pipe	Ref. P, h, $\dot{m}$	Ref. P, h, $\dot{m}$
f	FAN	Air P, T, RH Operating RPM	Air P, T, RH, $\dot{m}$
g	Drum	Air P, T, RH, $\dot{m}$ Operating RPM	Air P, T, RH, $\dot{m}$

Fig. 7 Heat pump dryer system dynamic model in Dymola.

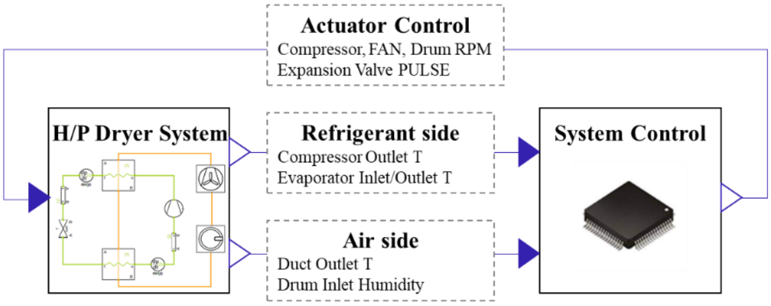
3.5. System Controls

In the heat pump-based dryer, the control strategy at starting point is determined depending on the amount of moisture in the clothes initially detected. The compressor frequency is controlled to adjust the drying level, and also the opening of the electronic expansion valve is controlled based on the level of super-heating at compressor suction port. In addition, the fan rpm be set to control the circulating flow rate on the air side, and the rotation speed of the drum is controlled for drying the clothes. Pre-defined algorithm determines the end time by checking the moisture amount of the clothes. Generally, the compressor operating frequency is the most influential factor on the cycle behavior. When the dryer started up, compressor frequency maintains at a high to maximize drying performance for a while. Resulting that the temperature of the circulated air raised as much as the increased pressure difference between evaporation and condensation. However, high frequency mode couldn't be kept long because the cloth may be damaged by overheating or might be happen to reliability issue of compressor. There has a protection algorithm to control compressor frequency not to cross the specific value based on the outlet temperature of compressor and a target frequency depends on it as well. The reference temperatures for frequency control is pre-defined according to the cloth and operation mode. The control logic for compressor frequency is shown in Figure 8 (a). In the study, input/output variables of control logic for cycles implemented from a dryer product were defined, and all sensors implemented in the product were modeled for connection with the heat pump system model. As shown in Figure 8(b), the control model for cycles receives a feedback from the heat pump model based on the information of the air and refrigerant state, and then the model for cycle control provides a command signal to the heat pump model through the interface, it should be a compressor frequency, EEV opening, and RPM target values of fan and drum at real-time. Finally co-simulation between the heat pump system model and the control model was performed as an entire system model.



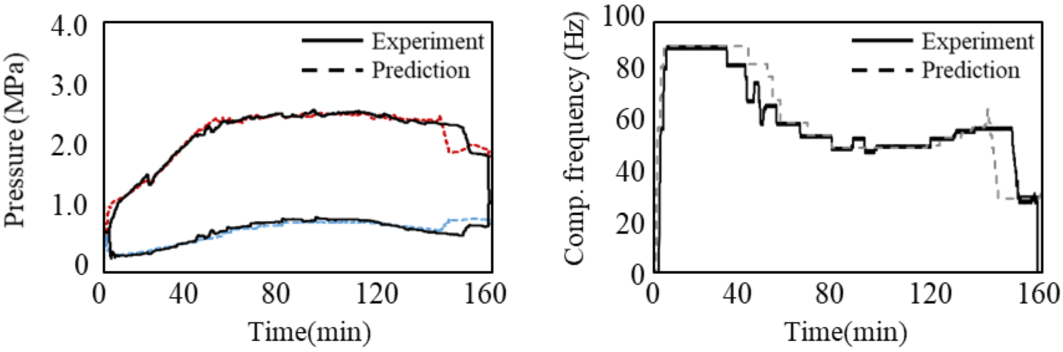
(a) Control strategy for compressor frequency

.



(b) Co-Simulation of integrated system model in Dymola

Fig. 8 The concept of co-simulation between control logic for cycles and heat pump system.



(a) Refrigerant pressure (b) Compressor frequency

Fig. 9 The comparison between experiments and predictions for 10kg load.

4. Simulation results and discussion

The validation of the heat pump-based dryer system model is confirmed by whether it predicts well by the change of air and refrigerant cycles according to the change in compressor frequency. The drying process can be defined into three stages. The first stage is a heating section where the drying speed increases as the temperature of the clothes rise to the wet bulb temperature, followed by a constant drying section as a second stage where the surface temperature of the clothes is maintained at the wet bulb temperature, and finally a reduction drying section where the surface temperature of the clothes rises to the dry bulb temperature of the dry air. The result of the simulation to the pressure of the refrigerant cycle under the load condition of 10 kg, it showed an error of 5% during the first and second stages, and it showed about 8% during the reduction section as a last stage. There observed a gap between prediction and experiment as time goes on as shown in Figure 9. The output values from the control model for cycles will be varies depending on the feedback values from the heat pump model in real time. If there happened an underestimation of the discharge temperature of the compressor from the model, it caused an error to predict proper frequency because the compressor frequency be determined by the discharge temperature of compressor during the stage of heating and constant drying as well. Moreover, the cycle control criterion for determining the completion of drying during the reduction drying stage set to the amount of moisture in the fabric. If the amount of fabric moisture is under predicted, there occurred a time difference to reach the minimum operating frequency. The amount of fabric moisture is determined by predicted values of air and refrigerant properties from heat pump system model at the initial stage of drying, in case there has an error and it accumulated continuously as time goes on, it affects the cycle control in the second half of drying. Therefore, the overall error of drying performance is the result of accumulated errors of the physical models for each component. Accuracy of the model for the drying performance depends on the prediction accuracy both of drying time and power consumption with various loads for the clothes. Three sorts of loads for the clothes from 5kg to 20kg were compared, where the drying time was calculated based on the time it took to reach the final moisture content from the initial moisture content of 60%. As the load of the clothes increased, the drying time and accumulated amount of electric power tended to increase as well. When it compared to the experiment, the drying time showed an error of 10%, and the accumulated power consumption showed an error of up to 7%.

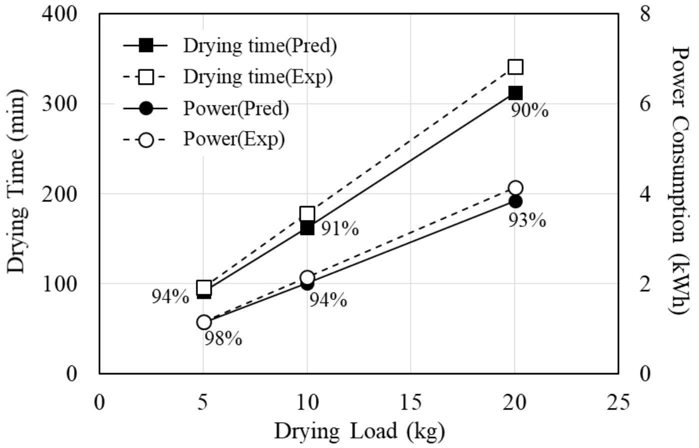


Fig. 10 Validation of the drying time and accumulated power consumption according to drying load

To make a further improvement of prediction to drying performance of the model, there have to consider a couple of things as follows. Because the rate of moisture content is the critical value for decision to system control during the drying process, accurate prediction of it serves as the most important factor in predicting the drying time and power consumption. Therefore, in order to improve the accuracy of the simulation, it is necessary to enhance the precision of the electrode sensor that measures the moisture content equipped in a product. In addition, the structure of the airflow path consist of a series of ducts, so it is necessary to more considering to leakage loss between components. And add a heat loss model to the current model can be a good way for improving accuracy because there has a heat transfer between product and environmental condition where it installed.

5. Conclusion

In the study, a dynamic model where combined a functional model and geometric model, was developed to predict the dynamic performance of the heat pump-based dryer system as a design tool. The model has verified that it simulates the drying performance well and control logic works accurately to the changes in various operating conditions. The decision of the end of drying be set at the high load condition because the prediction result of the rate of moisture content shows a relatively not a good accuracy at the condition. From based on this, it was confirmed that the error of the drying time and power consumption was up to 10% and 7%, respectively.

The main contributions brought by the modeling and simulation is that 1) The dynamic model for dryer system can be useful as a platform for design that can shorten the development time by optimizing the design parameters for the target performance in the earlier stage of product design. 2) The dynamic model for dryer system is a combined model where control algorithm and heat pump cycle, it can contribute to find the optimal algorithm scenario without or minimal testing by trying the maximum number of algorithm scenario cases at all design stages. 3) The dynamic model for dryer system consist of a functional model as well as a geometric model, there is flexibility to check the performance in advance by exploring various types of structures without relying on tests when structural or physical changes occur in the air flow ducting system. Finally, due to high energy efficiency, the demand for heat pump type dryers keeps on increasing, and the need for this model is even greater because there are many demands for responding quickly to the complexity and diversity of products in market. The result of the study can be applied very similarly to the washing machine system whose have a washing drum.

References

[1] Aceves-Saborio S, 1993, “Analysis energy consumption in heat pump and conventional driers”, Heat Recovery Systems &CHP, Vol.13, 419-428.

[2] A. Chailoet, T. Kliniam, R. Muangpisan, P. Kiatkungwankai, T. Leephakpreeda, 2010, “Analytical and Experimental Studies of Rapid Cloth Drying for Technological Innovation”, 2nd International Conference on Mechanical, System and Control Engineering, Moscow (Russia), June 21-23.

[3] Xiang C, Jing Z, Zhen Y, Liang S, Chun Z, 2021, “Process simulation and analysis of a closed loop heat pump clothes dryer”, Appl. Therm. Eng. 199 (2021) 117545

[4] C. Park, H. Cho, Y. Lee, Y. Kim, 2007, “Mass flow characteristics and empirical modeling of R22 and R410A flowing through electronic expansion valves”, Int. J. Refrigeration 30, 1401-1407.

[5] N.-H. Kim, J.-H. Yun and R. L. Webb, 1997, Heat Transfer and Friction Correlations for Wavy Plate Fin-and-Tube Heat Exchangers, *Journal of Heat Transfer*, Vol. 119, pp. 560~567

[6] Y. T. Lin, Y. M. Hwang, and C. C. Wang, 2002, Performance of the herringbone wavy fin under dehumidifying conditions, *International J. of Heat and Mass Transfer*, Vol. 45, pp. 5035-5044

[7] D. Lee, M. Lee, M. Park, Y. Kim, 2022,”Experimental evaluation and prediction model development on the heat and mass transfer characteristics of tumble drum in clothes dryers”, Appl. Therm. Eng. 202 (2022) 117900.

[8] Y. Do, M. Kim, T. Kim, S. Jeong, S. Park, S. Woo, Y. Kwon, Y. Jung, J. Lee, Y. Ahn, 2013, “An experimental study on the performance of a condensing tumbler dryer with an air-to-air heat exchanger”, Korean J. Chem. Eng. 30, 195-1200.

[9] K. Lee, J. Lee, Y. Hwang, M. Park, S. Oh, 2022, “Development of heat pump dryer system model through integrating thermodynamic model and data learning model”, SAREK Annual Conference 2022

[10] W. Kim, J. Lee, K. Lee, Y. Hwang, M. Park, S. Oh, 2022, “Data driven model of circulation air flow rate for heat pump dryer”, KSME Annual Meeting 2022