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Measurements of Evaporation and Condensation Mass Transfer Resistances for Surfaces in Residential Dishwashers

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ABSTRACT

During the drying phase of a dishwasher, water evaporation and condensation phenomena take place. Some wet surfaces inside the dishwasher are above the local air dewpoint and will experience evaporation, while other surfaces are below the local air dewpoint and will experience condensation. In this study, the evaporation mass transfer resistance of a standard load used in a household dishwasher was experimentally measured. The standardized load measurements were taken *in situ* during a regular drying phase after the ordinary washing was complete. To determine the mass transfer resistance of condensation, a tub wall sample was cut from the interior of a commercially available dishwasher. The wall samples were tested *ex-situ* in a benchtop psychrometric chamber to determine the condensation heat and mass transfer coefficient. The wall samples were locally cooled using a thermoelectric module. The experimental results were compared to those from a heat and mass transfer resistance correlation. The measured evaporation and condensation mass transfer coefficients can be used to model the drying process in a humid and stagnated environment.

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1. INTRODUCTION

Energy-efficient appliances are becoming essential due to increased energy demand worldwide and dishwashers are a common household with ~3% of the US's residential primary energy use (Bansal *et al.*, 2011). The energy efficiency of dishwashers could be promoted by advanced control units, improved food filters, reduced overall water consumption, high-efficiency motors, increasing cabinet insulation, or enhanced drying cycle. Drying is an energy-intensive process, and drying process advancements are critical for energy efficiency and customer satisfaction - the shortest dry time and energy consumption are the goals.

The drying in current dishwashers happens under forced and free convection to promote evaporation, while condensation occurs on tub walls to promote enhanced drying of the dishware load. In dynamic operations, a fan is implemented into the design to circulate air via forced convection, and in static operations where no fan is implemented, the momentum of the air is due to natural convection (Bengtsson & Berghel, 2017). In addition to the airflow, the dishwasher door is sometimes exploited to control the humidity in the tub. In an open method, the door is slightly opened when drying starts to let humid air escape into the environment. In a closed method, the door remains closed in the entire drying cycle. The combination of these options yields different drying performance as the drying is a complex function of mass, heat, and momentum transport. Herein, the mass transport from the dishware is of critical importance to enhance the understanding of its impact on the drying performance as well as to aid the modeling efforts of the dishwasher cycle performance.

Only two studies have been published for stationary droplet evaporation in stagnant air, for the combined effects of vapor phase natural convection and diffusion control of evaporation. Cioulachtjian *et al.* experimentally studied the effect of moist air and saturated vapor conditions on a horizontal plate (Cioulachtjian *et al.*, 2010). Leqoc *et al.* studied the effect of relative humidity between 50 and 85% together with air velocities and temperature of droplet evaporation on a stainless steel plate (Lecoq *et al.*, 2017). Similarly, there were few references for condensation on stainless steel plates at conditions experienced inside dishwashers during the drying cycle. The convection coefficients determined by Griffith & Hewitt, 1990 were found to be most similar to the experimental data found at the highest temperatures and relative humidity's reached at the end of a rinse cycle.

In this study, our goal is to evaluate the mass transfer resistance to the dishware experimentally. The evaporation resistance was measured *in-situ* inside a dishwasher tub, and the condensation resistance was measured *ex-situ* using a custom-built condensation chamber.

2. EXPERIMENTAL SETUP

2.1. The Evaporation Performance

The mass transfer resistance of individual dishware and the remaining water content of the load's top and bottom rack were experimentally measured in the dishwasher tub. During the drying phase, water evaporates off the load and condenses on the dishwasher tub walls as the outer surfaces of the dishwasher are cooled by contact with ambient air resulting in the temperature of the dishware is higher than the temperature of the tub walls. The mass transfer resistance of individual dishware was measured with a string-load-cell balance, as shown in Figure 1. In this setup, an individual dish or plate was suspended from the load cell, and its change in mass was measured with time as evaporation and drying occurred. The experiments were repeated five times to reduce the likelihood of errors and refine experimental observations. The relative humidity and dry-bulb temperature were measured during the drying phase at the top of the dishwasher with a humidity meter (HMT 337). The temperature on the load was measured with a T-type thermocouple adhered to the surface.

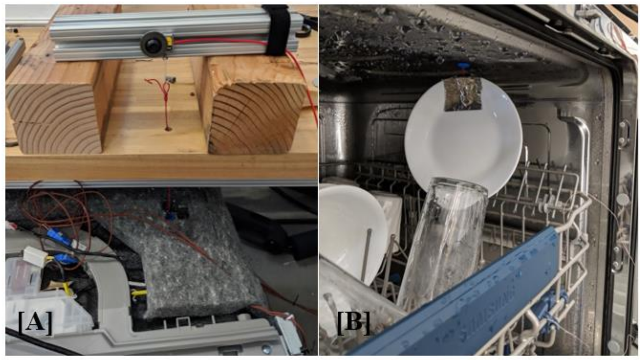

Figure 1. The mass transfer resistance measurement of individual load during the drying phase. (A) The load cell installation. (B) Suspension of the load inside the dishwasher.

For the experiments conducted to measure the evaporation rate from the entire dish load, the remaining water content of the dishware loads at the top and bottom racks during the drying phase was measured using load-cells installed on each corner of the rack, as shown in **Figure 2**. The temperatures of dishware were measured with a T-type thermocouple attached to the surface of each load with a high thermal conductivity epoxy.

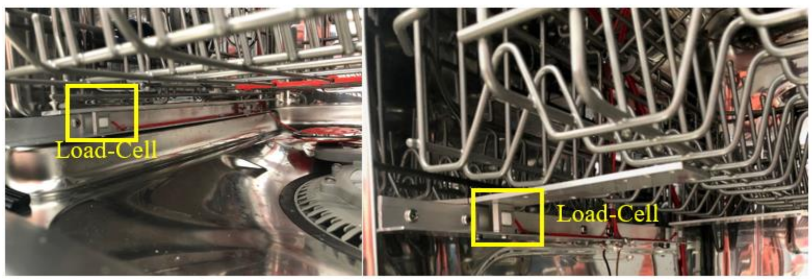

Figure 2. In-situ measurement of the remaining water content on the top and bottom racks and loads. (Left) Load cell installation on the bottom rack. (Right) Load Cell installation on the top rack.

In the experiments, the temperatures were measured using T-type thermocouples with an uncertainty of ± 0.5°C. The relative humidity of air was measured using a HMT 337 with an uncertainty of ± 1.0 % RH (0 – 40 % RH). The temperature of the air was measured using a Resistance Temperature Detector with an uncertainty of ± 0.1°C. The uncertainty on the load cell measurement (LSB 210) was ± 0.2%.

Table 1 summarizes various test conditions used to evaluate the drying performance of the dishwasher. In the baseline experiments 1, 2, and 3, no cooling and air circulation was provided during the drying process. As the baseline unit had no capability to provide cooling and air circulation. In experiments 3, 4, and 5, the dishwasher tub's interior was cooled with a thermoelectrical heat pump and modified to provide air circulation to reduce humidity stratification. The test sequence was started with the most passive solution of a vent that allows air to recirculate from the top to bottom of the tub through a vent in the door. The sequence enabled direct comparison of dishwasher drying features with and without active cooling.

Table 1: The test sequence for validating the drying performance under different test conditions.

Experiment	Cooling	Door Prop	Vent	Circulation
1	No	No	Yes	No
2	No	Yes	Yes	No
3	No	No	No	No
4	Yes	No	Yes	No
5	Yes	No	Yes	Yes
6	Yes	Yes	Yes	Yes

2.2. The Condensation Performance

A small humidity chamber was created to house the 40 x 40 mm wall sample, which was cooled to 10 °C by a thermo-electric (TE) module to condense water on the sample's surface. The surface temperature was kept constant by a proportional–integral–derivative (PID) controller that changed the power supply output to the TE. Saturated steam was pushed into the chamber by passing compressed air at 2-5 L/min through a two-gallon hot-water tank. The mass of the condensate falling from the surface of the wall sample was measured outside the chamber through a small channel, as shown in Figure 3. The 40 x 40 mm sample material of the dishwasher tub wall is shown as the green rectangle in Figure 3.

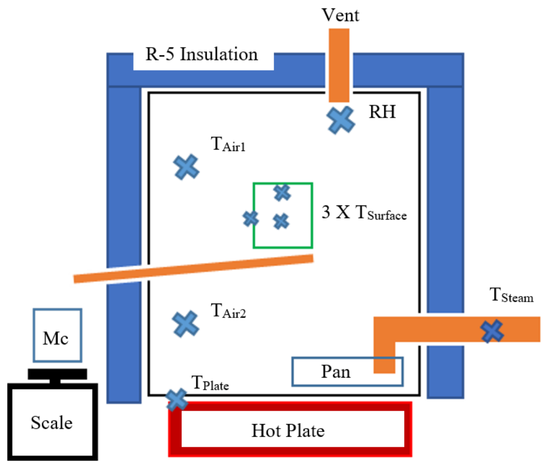

Figure 3:Schematic of condensation experimental test apparatus.

Saturated-water inlet temperatures greater than 60°C were maintained, and high relative humidity (>98%) was measured by a humidity meter (HMT 337) probe for all experiments. Surface and air temperatures were also recorded via type T thermocouples, as shown in Figure 3, to ensure the relatively constant temperature of the dishwasher wall sample and monitor the other system points. For elevated dew points (> 35°C), the hot plate was activated to increase the dry-bulb temperature and keep the humidity chamber free of condensation. Condensation rates at four different wet-bulb temperatures were tested until ~2 g of water was collected. The condensate was harvested from a drip-edge and channeled to a vessel for weighing scale with 0.0001 g uncertainty. The sample went through a series of condensation stages. Initially, the sample was loaded with a light fog (not shown), then small drops were produced on the surface, and finally, the drops coalesced into drips, as shown in Figure 4.

For the shorter experiments at higher dewpoint, the experiments were conducted once a steady state was reached (e.g., there was an initial loading on the plate). For these experiments, the initial and final loading was similar. For experiments at lower dewpoint temperature (< 35°C), the final loading on the plate was collected and added to the water collected during the experiment's timed portion. The condensation rate measured on the 40 x 40 mm sample is promising for a test at full scale. All experiments were run until about 2 ml of condensate was collected. The drying performance, which includes evaporation from the load and condensation on the TE sink, are discussed in the Results section.

Figure 4: Condensation stages from left to right, 1) before steam enters the chamber, 2) initial condensation (fogging and small drop formation), 3) drop coalescing into drips, and 4) condensate load on plate observed at the end of the experiment.

2.3. Equations and Correlations

The mass transfer resistance (R_m) of the individual load is calculated using the difference in load and ambient vapor pressure and mass change rate over 25 minutes.

$$R_m = \frac{P_{ws,dish} - RH * (P_{ws,amb})}{\dot{m}} \tag{1}$$

The relative humidity (RH) was measured by a humidity meter (Vaisala, Model HMT 337). The vapor pressure of water on the load ($P_{ws,dish}$) was taken as the saturation of water pressure at the measured temperature of their corresponding location. The vapor pressure of water in the air was calculated by multiplying the saturation pressure of water at ambient temperature ($P_{ws,amb}$) by the relative humidity (RH) of the air. Where, $\dot{m}$, the rate of mass change measured by the string load-cell balance was mean averaged every two minutes to reduce the measurement noise.

The in-situ measurement of remaining water on the dishwasher's top and bottom racks and loads were reported as remaining water content (RMC), as listed:

$$RMC = \frac{m_{total} - m_{dry}}{m_{dry}} \tag{2}$$

where (m_{total}) is total mass of the top and bottom racks, which were measured by the eight load cells. The dry mass (m_{dry}) is the mass of the racks and loads before the wash phase.

The saturation pressure P_{sat} (T) is derived from Antoine's equation (Himmelblau & Riggs, 2012), as listed:

$$In\left(\frac{P_{ws}}{1.333 \times 10^2}\right) = A - \frac{B}{C + T} \tag{3}$$

Where A = 18.3036, B = 3816.44, C = -46.13, and T is the surface temperature of the load.

The global heat transfer coefficients were calculated and compared to the *ex-situ* measurements from the small environmental chamber. In Rohsennow's 1998 heat transfer book, it is reported that compared to pure steam, steam-air mixtures have orders of magnitude lower global convection coefficients than for dropwise condensation (DWC) when small percentages of non-condensable air (e.g., <10%) are present in the system (Rohsennow *et al.*, 1998). The dewpoints experienced in dishwashers correspond to air percentages larger than 90%, and the convection coefficients should be drastically lower than those seen in theory for steam condensation. Chung et al., 2004 reported that filmwise convection coefficients are higher than DWC coefficients for steam in the presence of 6.5% air and 10 to 30 ºC subcooling, which is very much the case for dishwashers (Chung et al., 2004). Rose, 1981 reported that the global heat transfer coefficient is also affected by the condensate drop size (Rose, 1981). Castillo et.al. studied drop sizes and found divergence from the power-law as the length of their studies approached 90 minutes for a relative humidity at 70% (Castillo *et al.*, 2015). This divergence from the power-law should happen in shorter periods of time for the high RH's (e.g., >90%) found in dishwashers. The differences in conditions from a dishwasher to the highly sought after dropwise condensation in the presence of steam resulted in large differences in expected performance.

The three references found for global thermal coefficients of heat and mass transfer for dropwise condensation span three orders of magnitudes by simple comparison. The independent variables used in the correlations shown in Table 2 are saturated driving temperature (Griffith & Hewitt 1990), gas temperature in the case of equation 14.1 in Rohsenow et al., 1998, or saturation pressure in equation 14.2 (Rohsenow *et al.*, 1998).

Although the global heat transfer coefficients for dropwise and filmwise condensation are comparable in the presence of air, a significant film did not appear in the *ex-situ* studies as the surface properties of the dishwasher were hydrophobic and cooling power never reached the levels required to develop a film.

Table 2: Global Convection coefficients based on references.

Dew Point Temperature (°C)	28	34	42	47	**Intended use**
Griffith & Hewitt 1990 Convection Coefficient ($kW{\cdot}m^{-2}{\cdot}K^{-1}$)	108	121	137	146	$20 < T_{sat} < 100$ ºC
Rohsenow *et al.*, 1998 Fig 14.2 - extrapolation ($kW{\cdot}m^{-2}{\cdot}K^{-1}$)	23	28	29	31	100% steam over stainless steel

The latent heat of vaporization (h_{fg}) can also be modified by the specific heat of the liquid, a small subcooling temperature difference due to a film condensation, or the presence of noncondensible gases.

$$h'_{fg} = h_{fg} + cp * \Delta T \quad (6)$$

The resistances to mass transfer (R_{mt}) was calculated by converting the thermal coefficients of heat transfer into mass resistances by setting the condensation rate measured in the experiment to the pressure difference resistance eq. (7). Where A is the area of heat and mass transfer from the experiment, ΔT is the measured difference in the dew point and heat transfer surface, *dt* is the length of the experiment, ΔP is the difference between the measured air saturation temperature and the surface saturation temperature. The conversion from the global heat transfer h_{cnd} (Griffith & Hewitt, 1990) to R_{mt} coefficient as shown in equation 8.

$$\frac{\Delta P}{R_{mt}} = \frac{\dot{m}}{A} = \frac{h_{cnd} \Delta T/dt}{h_{fg}} \quad (7)$$

$$R_{mt} = \frac{\Delta P h_{fg}}{h_{cnd} \Delta T/dt} \quad (8)$$

The results will show at high dewpoint temperature the Griffith & Hewitt, 1990 correlation for h_{cnd} was the most appropriate choice for the dishwasher tub sample.

3. Results

3.1 Experimental Condensation Results

The condensate produced by a 40 x 40 mm sample was initially considered minimal. However, the amount of condensate was comparable when it was scaled to the size of the dishwasher, where the load of water on the dishes are relatively large. The average temperatures, standard deviation, calculated condensation rate and uncertainty, duration of the test, and condensation driving potential are reported in Table 3.

Table 3: Measured average values with standard deviations and calculated driving pressure for condensation.

Parameters	**Units**	**Test 1**	**Test 2**	**Test 3**	**Test 4**
$\mathbf{T_{surface}}$	°C	10.1	9.94	10.2	17.5
Std $\mathbf{T_{surface}}$	°C	0.08	0.17	0.26	3.98
$\mathbf{T_{dew}}$	°C	28.02	34.12	41.92	47.02
Std $\mathbf{T_{dew}}$	°C	0.25	0.83	0.76	0.42
$\dot{\boldsymbol{M}}_{\mathbf{condensed}}$	g/hr	0.679	1.66	3.02	7.07
Uncertainty	g/hr	0.03	0.07	0.14	0.36
Duration of test	hrs	3.06	1.42	0.69	0.31
$[\boldsymbol{P}_{\boldsymbol{sat}_{\boldsymbol{air}}} - \boldsymbol{P}_{\boldsymbol{sat}_{\boldsymbol{surface}}}]$	Pa	2550	4137	6937	8428

The initial dewpoint condition in a dishwasher tub is typically around 50 °C and this condition was hard to replicate in the humidity chamber. As the dishwasher tub cools, the driving potential reduces, even at high relative humidity, and it takes three hours to condense 2 g of water. The initial condensation rate is critical in dishwasher drying – the impact of initial condensation on the drying of the loads is summarized in section 3.4.

3.2 Comparison of Condensation Correlations

Figure 5 compares the experimentally measured condensation mass transfer resistance to the correlation developed by Griffith and Hewitt (Griffith & Hewitt, 1990) at lower dewpoint conditions. As summarized, at dewpoints (> 40°C) near the conditions

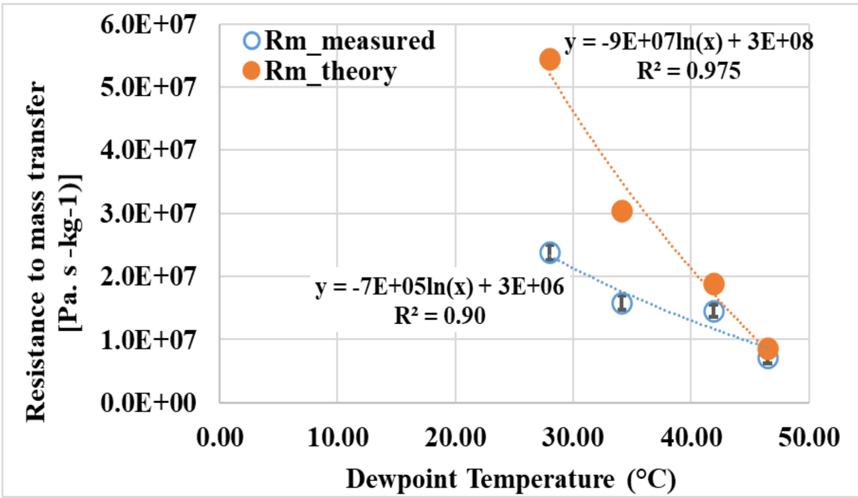

Figure 5: Measured resistance to mass transfer for a wall sample (open circles) and the expected resistance to mass transfer calculated from [12] (filled circles)

The difference between the measured and theoretical value of the mass transfer resistance is due to the decreasing resistance with time (e.g., the second ml of water was collected much faster than the first ml of water). The results suggest that the condensation rate was increased, and extra water was collected during the longer test periods. These findings suggest that a shorter time period while avoiding condensed water from other parts of the chamber entering the collection tube might improve the experiment. Average resistance to mass transfer for the saturation temperatures experienced in dishwashers for the length of the drying period could be used for modeling.

3.3. Mass Transfer Resistance of Individual Loads

Table 4 summarizes the mass transfer resistance of individual loads during the drying phase. The mass transfer resistance was averaged over 25 minutes. The variation in absolute mass transfer resistance between the loads was due to the difference in the load surface area, the load placement, and the material.

Figure 6 summarizes the top and bottom racks' drying performance under different drying test conditions reported in Table 1 over 28 minutes. The initial drop in the first two minutes was due to the DW unit's shaking while inserting the RH probe. Figure 6 (a) illustrates the drying performance of the DW unit's bottom rack without any additional cooling. In test 1, the DW unit's bottom rack was 45% dry without door prop, with 5.5 wt% of water remaining. With the door prop, the DW unit's bottom rack was 81% dry with less than 2 wt% of water remaining. However, with the door prop, the DW's moist air would condense on the kitchen top and cause damage and customer dissatisfaction. Therefore, the majority of the customers are unwilling to operate their dishwasher under a door prop mode.

Figure 6 (b) illustrates the top rack's drying performance without any additional cooling. In all three test conditions, the DW unit's top rack was 47% dry, with more than 2 wt% of water remaining after the first 20 minutes. Most of the top rack's drying was accomplished in the first two minutes during the initial shaking, furthermore, the high humid condition at the top of the dishwasher, reduced the evaporation rate at the top. The top rack's drying performance increased slightly with door prop with less than 1.25 wt% water remaining.

Table 4: The drying mass transfer resistance of the individual components in the load

Dish Settings	Rack Location	Quantity	Mass Transfer Resistance ($kPa \cdot s \cdot kg^{-1}$)	Surface area (m^2)
Dinner Plate	Bottom	8	12,098	0.09817
Bread and Butter	Bottom	8	9,986	0.04539
Fruit Bowl	Top	8	10,098	0.02654
Saucer	Bottom	8	11,058	0.03534
Serving Bowls	Bottom	2	14,998	0.08328
Serving Platter	Bottom	1	13,352	0.07765
Cutlery Set 1[a]	Bottom	8	7,591	0.03249
Cutlery Set 2[b]	Bottom	1	8,357	0.02144

[a] The cutlery set 1 includes dinner fork, salad fork, knife, spoon.
[b] The cutlery set 2 includes serving fork and serving spoon.

Figure 6 (c) illustrates the drying performance of the DW unit's bottom rack with additional cooling. The DW unit's bottom rack with cooling was 68% dry, with less than 3 wt% of water remaining. The additional cooling enhanced the drying at the bottom rack by 45.5 %. The additional cooling helped increase the rate of condensation in the DW tub. The drying at the bottom rack was further enhanced with circulation by 33.3%, reducing the hot, humid air stratification in the tub. We achieved complete dryness in the bottom rack with door prop and circulation. Figure 6 (d) illustrates the DW unit's top rack's drying performance with additional cooling.

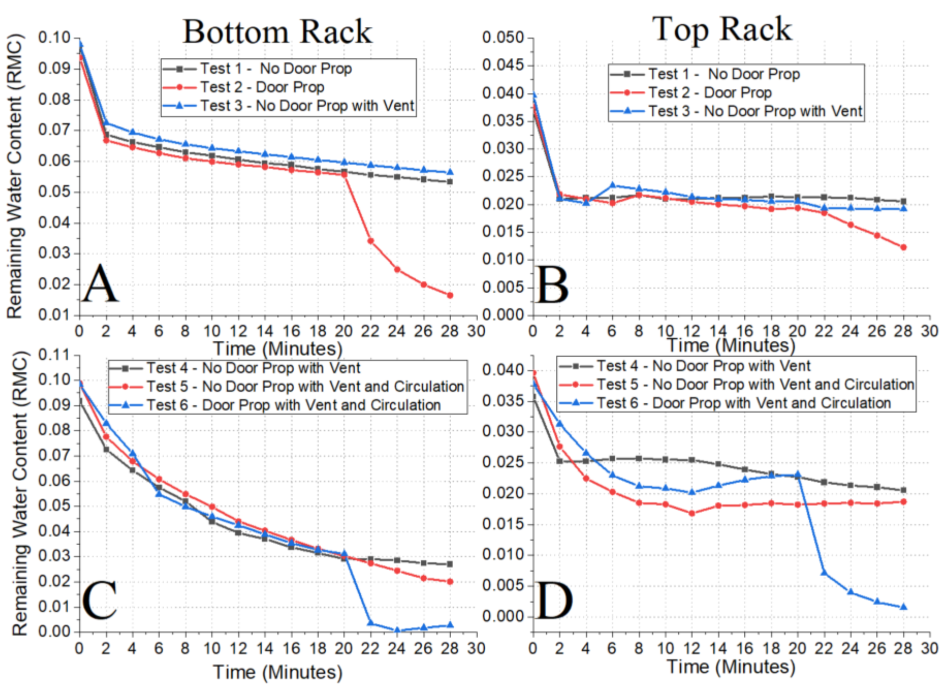

Figure 6. The dying performance of the top and bottom rack with and without cooling. (A) Bottom rack without cooling. (B) Top rack without cooling. (C) Bottom rack with cooling. (D) Bottom rack without cooling.

The top rack's drying was initiated after 12 minutes in the case without door prop and circulation. As it took 12 minutes for the ambient humidity near the top rack to drop below 100% (Figure 7). The drying was enhanced with circulation in the first 12 minutes, but after 12 minutes, the RMC increased and remained stable. The increase in RMC could be caused by droplets from the tub's top wall depositing on the loads and rack. Circulation helped maintain less than 100% RH at the top. With door prop and circulation, the top rack was 93% dry at the end of the 28 minutes, with less than 0.25 wt% of water remaining.

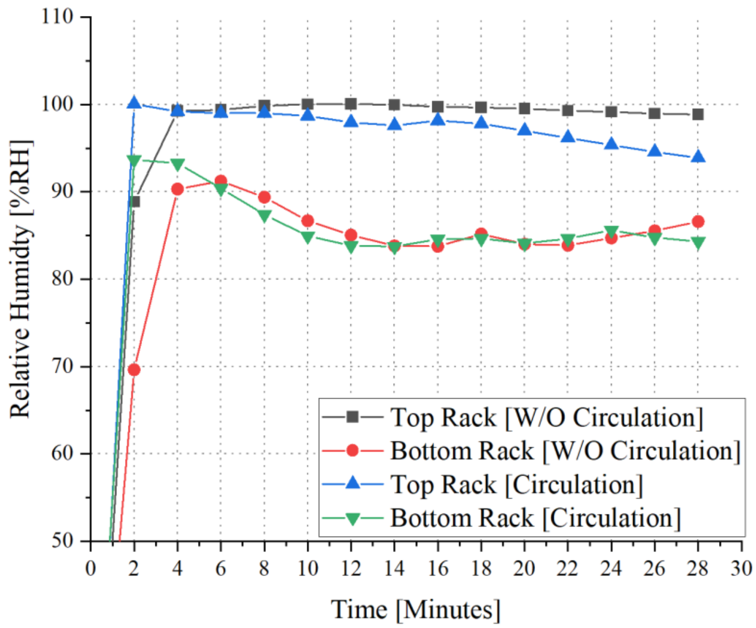

Figure 7: The relative humidity in the tub near the top and bottom rack during drying dishwasher

Figure 7 illustrates the stratification of humid air in the dishwasher during drying. Two distant stratification zone between the bottom and top rack were observed. The relative humidity of air near the bottom rack averaged around 85 %RH, whereas the top without circulation was 100 % RH during the first 12 minutes. With circulation, the relative humidity was reducing gradually over the 28 minutes.

4. CONCLUSION

The experimental determination of the mass transfer resistances of individual load in the dishwasher is of importance to enhance our understanding of heat and mass transfer phenomena in residential dishwashers. Therefore, in this study, the condensation and evaporation mass transfer resistance of the internal components of the dishwasher were experimentally measured. The evaporation resistances were measured *in-situ* with a static-closed configuration where the condensation resistance was measured *ex-situ* using a house-in-built condensation chamber.

The following conclusions are drawn from the *in-situ* experiments:

- No change was observed in the drying performance of the dishwasher with an addition of the dry vent
- The door-prop feature significantly (200% improvement) reduces the remaining water content (RMC) on both the upper and lower rack
- The water content on the top rack is lower than the water content of the bottom rack. Also, the evaporation rate on the top rack is slower than the bottom rack due to stratification.

The measurement of the mass transfer resistances could be rather challenging due to the nature of the experiments. For example, in the in-situ analysis, we observed the drops from the top of the tub onto the top rack, increasing the drying results' uncertainty. Similarly, in the *ex-situ* measurement, mimicking the high initial dewpoint dishwashers was somewhat challenging and arduous. Furthermore, the stratification could be minimized by the circulation of tub air while improving the drying performance by 60% at the top rack with an insignificant impact on the bottom rack's drying rate. Regardless of challenges and limitations, we believe the findings in this study enhances our knowledge on the heat and mass transfer phenomenon in dishwashers, which can be used to develop new dishwasher designs for improved drying performance as, to the best of our knowledge, the experimental measurement of mass transfer resistances of individual dishware during the drying phase in the residential dishwasher has never been reported.

NOMENCLATURE

The nomenclature should be located at the end of the text using the following format:

RH	Relative humidity	(%RH)
m	Mass	(g)
$\dot{m}$	Mass flowrate	(g/s)
P_{ws}	Saturation Pressure	(Pa)
h_{fg}	Latent heat of vaporization	(J/g)
h	Heat transfer coefficient	($W/m^2.K$)
R	Resistance	(Pa-s/g)
T	Temperature	(°C)
t	Time	(sec)
Cp	Heat capacity	(J/g-K)
RMC	Remaining water content	(wt fraction)

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