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Transient behavior of run-around heat and moisture exchanger system. Part II: Sensitivity studies for a range of initial conditions

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ABSTRACT

Part I of this paper [17] developed and verified the numerical model for simultaneous heat and moisture transfer in the run-around membrane energy exchanger (RAMEE) system to determine the transient behavior of the system under different initial and operating conditions.

This paper presents the transient response of the RAMEE system for step changes in the inlet supply air temperature and humidity ratio. Also the system quasi-steady state operating conditions are predicted as the system approaches its asymptotic operating condition. The transient responses are predicted with changes in various parameters. These include: the number of heat transfer units, thermal capacity ratio, heat loss/gain ratio, storage volume ratio and the normalized initial salt solution concentration. It is shown that the storage volume ratio and the initial salt solution concentration have significant impacts on the transient response of the system and heat transfer between the RAMEE system and the surrounding environment can change the system quasi-steady conditions substantially.

1. Introduction

The steady state behavior of heat exchangers is well established for simple configurations such as plate exchangers and heat wheels. Calculation methods for design of these exchangers are developed in detail [1,2]. For time varying inlet conditions, it is important to study the dynamic or transient behavior of heat exchangers to achieve reliable control strategies under different operating conditions.

Many investigations have been performed to show the dynamic behavior of single heat exchangers. Romie [3] analyzed the transient outlet temperature of two unmixed fluids leaving a cross-flow exchanger. Using Laplace transform, the response was found with large wall capacitance for a step change in the inlet temperature of either fluid. He also investigated the impact of all the dimensionless parameters used in the governing equations. Spiga and Spiga [4] presented solutions for the two dimensional transient temperature distributions in the core wall and in the both unmixed fluids following a step change at the inlet of the primary fluid of a cross-flow heat exchanger. The assumption of large capacitance was no longer made in this analysis and with finite wall capacitance the solutions were provided as simple integrals of Green's function using the threefold Laplace transform method. To avoid the complexity of two- and threefold Laplace transform, Chen and Chen [5] analyzed the transient behavior of cross-flow heat exchangers with finite wall capacitance by using single Laplace transform only with respect to time in conjunction with power series technique. Romie [6] gave the transient response of cross-flow heat exchangers for which the thermal capacitance of the wall is negligible compared to the ones for the fluids. A step input disturbance was provided in the hot fluid inlet temperature where a threefold Laplace transform was used to solve energy balance equations for two fluids.

Mishra et al. [7] studied the transient behavior of cross-flow heat exchangers in presence of two dimensional conduction in wall and axial dispersion in fluids. They used a finite difference formulation to solve the governing equations for a step, ramp and exponential change in the inlet temperature of hot fluid. It was shown that that longitudinal conduction has a significant impact on the transient temperature when a high NTU is used. In addition, the effect of axial dispersion becomes important when *Pe* is small. Mishra et al. [8] also investigated the transient response of the three-fluid cross-flow heat exchangers with both large and finite wall capacitance. In their model, all the fluids were unmixed and step, ramp, exponential, and sinusoidal disturbances of the inlet temperature were provided for the central fluid entrance condition.

The heat exchangers can be utilized as coupled sub-system using a coupling fluid circulated by a pump [9]. This run-around heat recovery system, also called liquid-coupled indirect transfer-type exchanger system, has been used in industry for many decades.

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Nomenclature

C	heat capacity rate [W/K]
C_{Salt}	concentration of salt solution (kg of salt per kg of solution) [%]
NTU	number of heat transfer units for each exchanger
Pe	Peclet number
t	time [s]
T	temperature [K]
W	humidity ratio [kg_v/kg_{Air}]
X	ratio of water mass to mass of pure salt [kg/kg]
Greek symbols	
ε	effectiveness
η	number of liquid desiccant circulation within both exchangers of a run-around system required to reach quasi-steady state condition
μ	initial ratio of mass of salt (solution) in the exchangers to the total mass of salt (solution) in the system
σ	heat loss/gain ratio which represents heat loss/gain rate relative to energy transfer rate within a exchanger
τ	dimensionless time of a run-around system defined relative to the transport time for the bulk solution to flow through both exchangers
Subscripts	
Air	air side
E	exhaust side
l	latent
S	supply side
Sol	salt solution
s	sensible

The dynamics behavior of a run-around system was studied [10], and it was estimated that the time constant of these systems is typically much less than for typical changes in the weather. Ranong et al. [11] analyzed the steady state and transient behavior of a system consisting of two exchangers coupled by circulating fluid. The transient response of the system with a step change in the coupling fluid mass flow rate was studied. The system response calculated by the method of Laplace transforms and explicit finite difference method showed that the outlet temperature of external flows oscillate with reducing amplitude after a step change in mass flow rate of coupling fluid to reach a new steady state condition. This finding implied that the transient behavior of a coupled system was different from single heat exchanger where no oscillations are observed.

In the last two decades, extensive research has been performed on the energy wheels which can transfer not only heat but also moisture between supply and exhausts air steams as air-to-air energy recovery systems in HVAC applications. Simonson and Besant [12] studied sorption, condensation, and frosting in rotary energy exchangers by a transient numerical model for coupled heat and moisture transfer. It was found that reducing the wheel speed reduces uncontrolled condensation and frosting. Abe et al. [13,14] developed mathematical models for predicting the characteristic time constants, as well as, the effectiveness of an energy wheel using only the expected transient response functions. A run-around membrane energy exchanger (RAMEE) described in Part I of this paper is a new alternative to air-to-air energy recovery system and unlike its steady state performance [15] no references are found for the transient behavior of the RAMEE system.

The objective of this paper is to use the verified mathematical/numerical model presented in Part I to determine the sensitivity of run-around system following step changes in the supply air temperature and humidity ratio. In order to select the most favorable desiccant fluid volumes in the system during hourly or daily changes in operating conditions, the thermal and mass transfer capacitance effects of the desiccant fluid must be investigated. To make the results of general use, dimensionless parameters are used throughout. The effects of various parameters, particularly the numbers of heat transfer units, thermal capacity ratio, heat loss/gain ratio, storage volume ratio and normalized initial salt solution concentration, will be studied.

2. Numerical model

A run-around membrane energy exchanger (RAMEE) system is comprised of two liquid-to-air membrane energy exchangers (LAMEE), two storage tanks, connecting tubing and pumps as shown in Fig. 1 in Part I of this paper.

A numerical model was developed from physical principles for simultaneous heat and moisture transfer in the RAMEE system in Part I of this paper. This numerical model was two dimensional for the cross-flow exchangers and was formulated using the finite difference method. The numerical model includes the reservoirs and their effects on the dynamic performance of the system. The assumptions made for investigation were (1) flows within channels are laminar and fully developed, (2) the heat and mass transfer processes take place only normal to each membrane, (3) axial heat conduction and water vapor molecular diffusion in the two fluids in the flow directions are negligible, (4) heat gain or loss due to adsorption/desorption of water vapor at the membrane surface occurs only in the liquid component, (5) the membrane properties are constant and its thermal and mass transfer capacitance effects are neglected, and (6) the salt solution in the reservoirs is well mixed at all times.

The dimensionless governing equations for coupled heat and moisture transfer in the RAMEE system based on the above assumptions were presented for each exchanger (LAMEE) in Eqs. (10)–(13) in Part I. The energy and mass balance of salt solution components within the storage tank were given in Eqs. (38), (39), and (42) in Part I. The heat loss/gain from/to the external liquid desiccant loop was included to account in the energy balance equation of reservoirs. By introducing boundary and initial conditions for temperature of the air and salt solution [$T_{Air(or\ Sol)}$], humidity ratio of the air (W_{Air}) and water mass fraction of salt solution (X_{Sol}), the numerical model solution gives the two dimensional temperature and humidity ratio (water mass fraction) distributions within both air and salt solution throughout each exchanger as a function of time. The effectiveness values were defined for both supply and exhaust side of the RAMEE system by Eqs. (56)–(59) in Part I based on the change in the airstreams properties. These effectivenesses are used to study the effect of various parameters on the heat and moisture transfer rates in the run-around system during the transient and quasi-steady state conditions.

To investigate the transient response and quasi-steady state performance of the RAMEE system, the dynamic performance of the run-around loop was studied for a time duration long enough to reach a quasi-steady state for each operating condition. The quasi-steady state criteria for the case of $\Delta C_{Salt} = 0$ were defined based energy and mass balances of the airstreams and presented in Eqs. (60) and (61) in Part I. For the case of $\Delta C_{Salt} \neq 0$, Eq. (62) in Part I was used as quasi-equilibrium criterion. This criterion determines the quasi-steady sate condition by considering the rate of changing

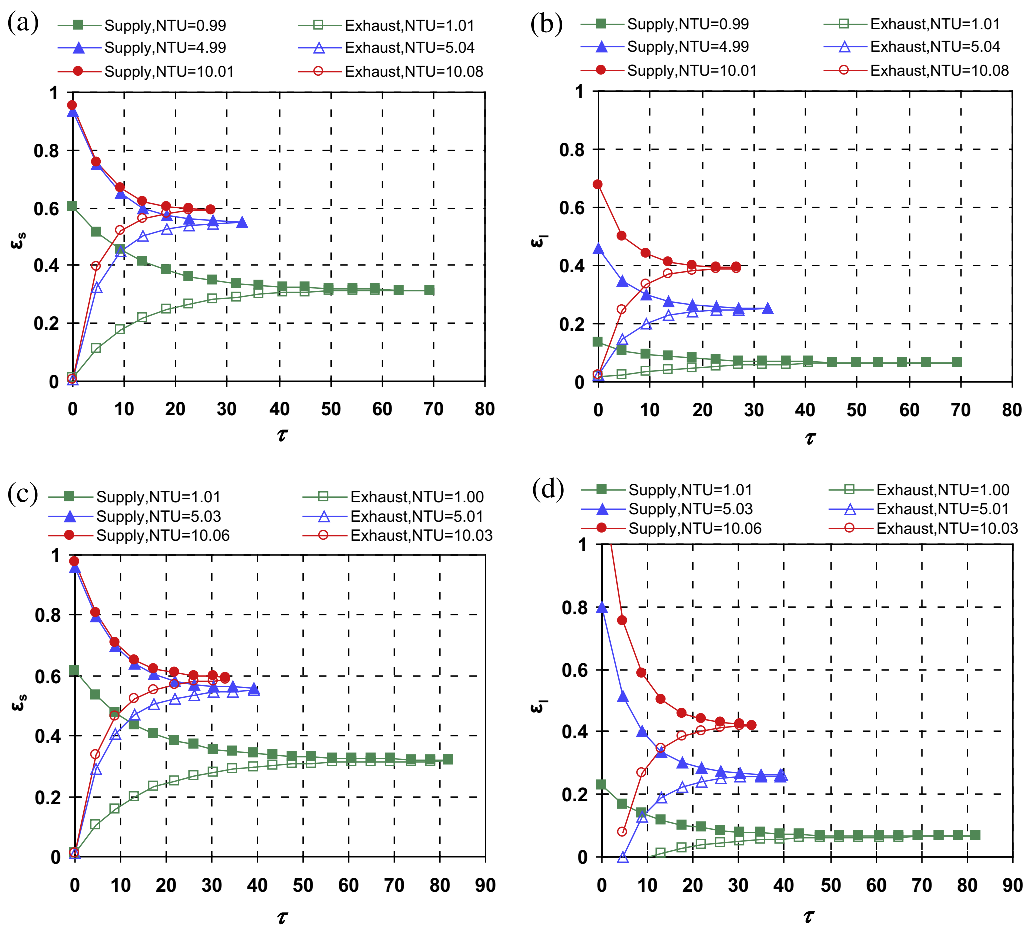

Fig. 1. Effectiveness of the RAMEE system for (a) sensible and (b) latent heat transfer during AHRI summer test conditions and for (c) sensible and (d) latent heat transfer during AHRI winter test conditions versus the number of liquid desiccant circulation cycles at different NTU values ($C_{Sol}/C_{Air} = 3$, $\mu = 0.15$, $\sigma = 0$, $\Delta C_{Salt} = 0$).

properties in the system that directly impacts the energy transfer rate.

3. Results and discussion

A parametric study is employed to investigate the transient performance of the RAMEE system consisting of two cross-flow heat and moisture exchangers with the parameters and properties of the LAMEE described in Table 2 in Part I of this paper. Results are presented for different values of NTU, C_{Sol}/C_{Air}, and μ for balanced air flow rates for a time duration sufficient to reach the above defined quasi-steady state operating conditions. As well, a finite heat loss/gain ratio is included in the RAMEE system to study the effect of external heat loss or gain on the performance of the run-around heat and moisture recovery system. Finally, an investigation of the initial salt solution concentration and its impact on the transient response of the RAMEE system is presented.

3.1. Effects of number of heat transfer units (NTU)

The effectiveness values change with time after a step change in the inlet conditions. The time it takes to reach quasi-steady state is strongly influenced by the operating conditions. Fig. 1 shows the dynamic behavior of the supply and exhaust exchangers at different operating conditions as a function of the number of the liquid desiccant circulations in the system, τ, which is a dimensionless characteristic time. Excluding the reservoirs and piping, the time for one circulation is the time required for the bulk mean properties of the salt solution to flow through both the supply and exhaust exchangers or the time for the salt solution in both exchangers to be replaced by the incoming fluid. For the RAMEE system consisting of two identical exchangers with parameters and properties used in the experimental comparison of this paper (see Part I), the real time (min) equivalent to one circulation depends on both NTU and C_{Sol}/C_{Air}. For instance, this time for one circulation is equal to 7.4 min where NTU = 5 and $C_{Sol}/C_{Air} = 3$.

From Fig. 1(a) and (b) (AHRI summer conditions), it is noted that approximately the same number of the liquid desiccant circulations are required to reach quasi-steady state for both sensible and latent effectiveness. The same conclusion can be made from Fig. 1(c) and (d) for AHRI winter conditions. Fig. 1 shows that, at quasi-steady state condition the effectiveness values for the supply and exhaust exchangers are the same due to mass and energy balance in the RAMEE system.

As shown in Fig. 1, the NTU for the supply exchanger is approximately equal to NTU for the exhaust exchanger. This is due to the fact that exchangers in the supply and exhaust side are identical and the fluid flow rates are equal. Nevertheless, due to the different properties of the air and salt solution in each exchanger this NTU value will slightly deviate (less than 0.1%) from the reported value. In the rest of this paper, the value of NTU is considered equal for both supply and exhaust exchanger and therefore, a unique value is reported.

The effect of the number of heat transfer units (NTU) on the transient response of the system at AHRI operating conditions [16] is more evident from Fig. 2. It should be reminded that NTU increases when the heat exchanger dimensions increase or the mass flow rate of air decreases (the mass flow rate of air is modified in this paper since the geometry of the LAMEEs is fixed). At low air mass flow rates, more time is required for the air within the channels to be replaced by incoming air. This causes the air and the liquid desiccant within the exchangers to have more time to exchange heat and moisture. As a result the RAMEE system requires a fewer number of desiccant circulations (η) to reach equilibrium. Therefore, an increase in NTU reduces the number of liquid desiccant circulations required for quasi-steady state to be reached. Fig. 2 shows that when NTU changes from 5 to 10, the number of circulations required to reach quasi-steady state decreases from 33 to 27 which implies 19% reduction for the AHRI summer operating conditions. Fig. 2 demonstrates that η decreases by more than 52% in both AHRI summer and winter operating conditions when NTU is increased from 1 to 5. On the other hand, the actual time or real time required to reach equilibrium will increase with NTU. It is shown that the real time required to reach quasi-steady state increases from 242.5 min (4.04 h) to 395 min (6.58 h) when NTU changes from 5 to 10 for the AHRI summer operating conditions. This occurs because the higher the NTU, the more slowly the run-around fluid is pumped for a given geometry of each exchanger in order to keep the same heat capacity ratio (C_{Sol}/C_{Air}) and the slower the RAMEE system will reach steady state condition.

3.2. Effects of heat capacity rate ratio (C_{Sol}/C_{Air})

The run-around system allows the pumping rate of the liquid salt solution to be selected arbitrarily, independent of the inlet air conditions. The effectiveness values [15] as well as the time required to reach steady state will vary with different salt solution mass flow rates in the RAMEE system. The higher pump flow rates result in an increase in the heat capacity rate ratio of the exchanger when NTU is kept constant for a fixed geometry. As seen in Fig. 3, the number of liquid desiccant circulations required to reach quasi-steady state decreases as C_{Sol}/C_{Air} decreases because the dwell time of the salt solution in the exchanger channels increases as C_{Sol}/C_{Air} decreases. This provides more time for the air and desiccant liquid to exchange heat and moisture during one pass of the liquid. Fig. 3 displays the number of times the salt solution must pass through both exchangers before quasi-steady state is achieved. At AHRI summer operating conditions, η is reduced by up to 81% when C_{Sol}/C_{Air} changes from 10 to 1 at NTU = 5.

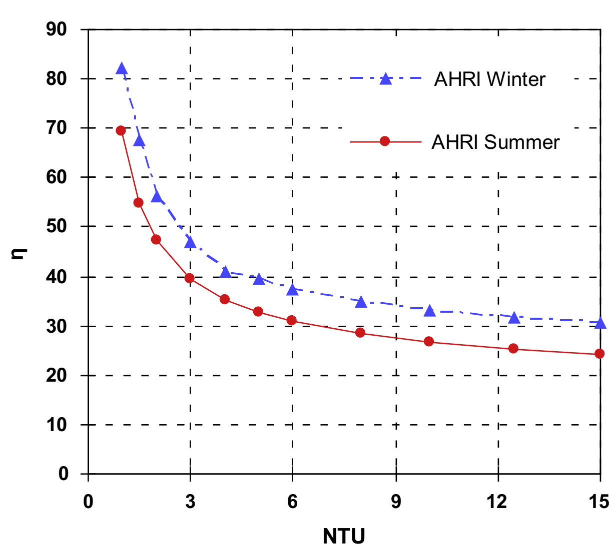

Fig. 2. Change in the number of liquid desiccant circulations to reach quasi-steady state for the RAMEE system due to different NTU values at AHRI operating conditions (C_{Sol}/C_{Air} = 3, μ = 0.15, σ = 0, and ΔC_{Salt} = 0).

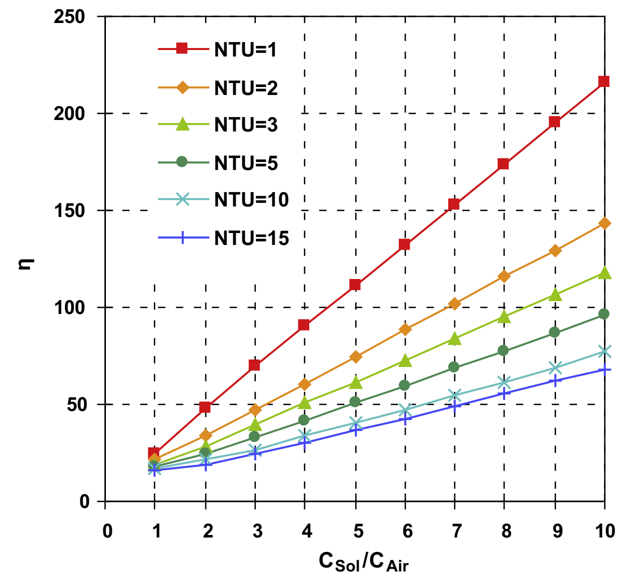

Fig. 3. Change in the number of liquid desiccant circulations to reach quasi-steady state conditions for the RAMEE system for different C_{Sol}/C_{Air} values with NTU as a parameter for AHRI summer operating conditions (μ = 0.15, σ = 0, and ΔC_{Salt} = 0).

In practical applications, the real time required to reach quasi-steady state is of interest and the HVAC engineer would need to know how this real time changes as the solution pumping rate changes. Although the number of circulations required for the salt solution to flow through both the supply and exhaust exchangers decreases from 96 to 17 for AHRI summer operating conditions when the C_{Sol}/C_{Air} value changes from 10 to 1, it is observed that the response time will increase from 212.7 min (or 3.54 h) to 387.5 min (or 6.46 h) in real time for the RAMEE system with two identical LAMEEs.

The change in the airstreams inlet conditions affects the dynamic response of the RAMEE system. A comparison between the AHRI summer and winter results is presented in Fig. 4(a). Fig. 4(a) shows that the RAMEE system reveals a similar behavior in both AHRI summer and winter conditions with an increase in the mass flow rate of the liquid desiccant in the exchangers where the other parameters are kept constant. However, there is a difference in the dimensionless time it takes the system to reach steady state. This response time variation between different operating conditions is believed to be caused by a higher change in the temperature that the liquid desiccant will undergo to reach quasi-steady state at AHRI winter operating conditions. The numerical model shows at NTU = 5 and C_{Sol}/C_{Air} = 3 the average change in the liquid desiccant temperature is 9.6 °C for AHRI winter operating conditions, while this change is observed to be 6.7 °C at AHRI summer operating conditions for the identical exchangers at the same NTU and C_{Sol}/C_{Air} values.

The various heat capacity ratio values, C_{Sol}/C_{Air}, not only change the transient response of the RAMEE system, but also the quasi-steady state effectiveness values. Fig. 4(b) reveals that the RAMEE system at AHRI summer operating conditions reaches its highest effectiveness at approximately C_{Sol}/C_{Air} = 3 which is in agreement with the previous finding [15]. It is also shown that the heat capacity ratio corresponds to maximum effectiveness of a run-around heat and moisture recovery system depends on the operating conditions so that the peak value occurs at a different C_{Sol}/C_{Air} value for AHRI winter operating conditions.

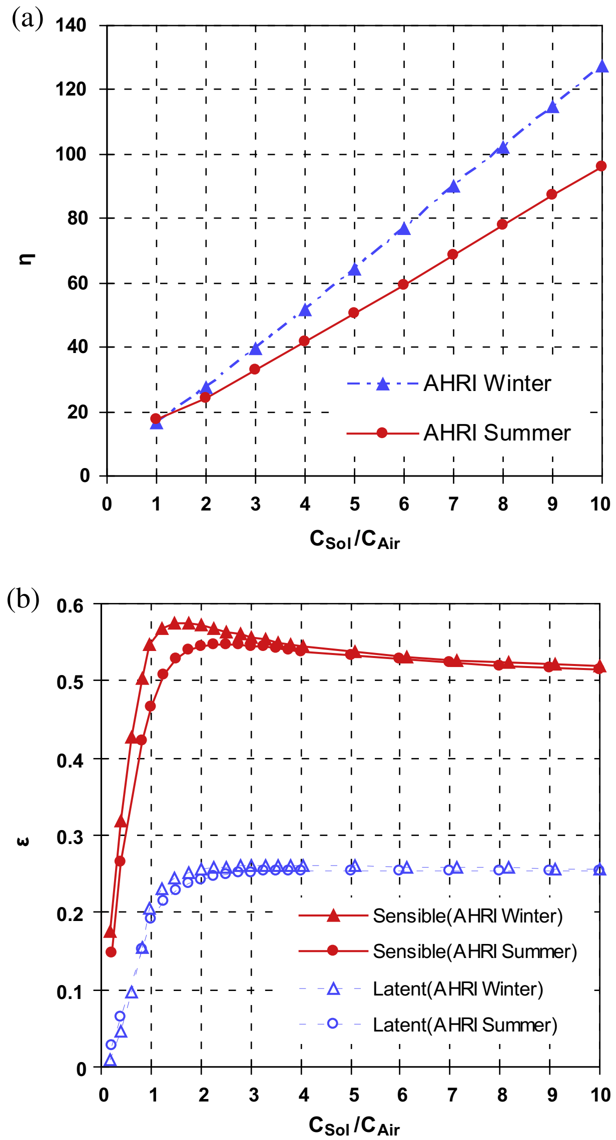

Fig. 4. (a) Change in the number of liquid desiccant circulations to reach quasi-steady state and (b) variation of the sensible and latent effectivenesses conditions for the RAMEE system for different C_{Sol}/C_{Air} values for different operating conditions (NTU = 5, $\mu = 0.15$, $\sigma = 0$, and $\Delta C_{Salt} = 0$).

3.3. Effect of storage volume of salt solution on the transient response (μ)

One of the aims of the present work is to study the effect of salt solution storage volume on the transient response of the RAMEE system. The size of reservoirs has a substantial impact on the rate at which the RAMEE system moves toward equilibrium as shown in Fig. 5. The presence of large reservoirs increases the mass of desiccant that must undergo a transient change in temperature and concentration. This increases the time it takes the system to reach equilibrium. Large time delays may be problematic for the operation of this HVAC system in climates where the temperature and humidity change frequently and by large amounts. In this study, a large storage tank corresponds to a smaller value of μ, where μ is the initial fraction of the mass of salt in the exchangers to the mass of salt in the entire system including exchangers, storage tanks and piping. Fig. 5 presents the effect of the initial mass fractions on the dimensionless time required to reach quasi-steady state (η) for both AHRI summer and winter operating conditions.

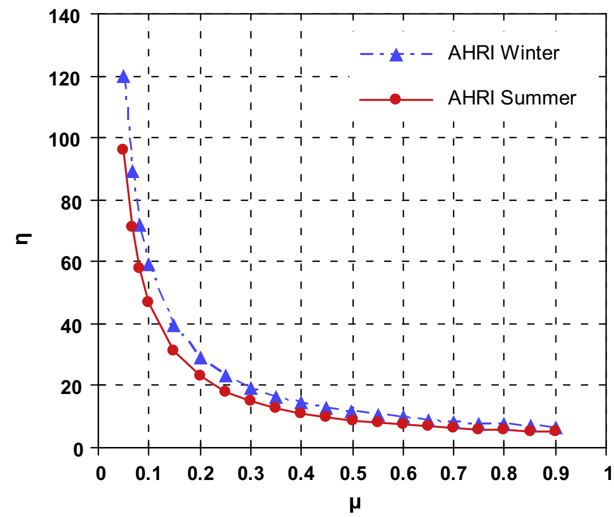

Fig. 5. Change in the number of liquid desiccant circulations to reach quasi-steady state condition for the RAMEE system due to different size of storage tanks for AHRI operating conditions (NTU = 5, $C_{Sol}/C_{Air} = 3$, $\sigma = 0$, $\Delta C_{Salt} = 0$).

This figure shows that an increase in μ from 0.15 (used in the experimental comparison in Part I) to 0.5, which corresponds to a 5.5 times reduction in the size storage tanks, results in a 75% faster response time for both AHRI operating conditions. This transient response could be reduced by a further 33% if μ is increased from 0.5 to 0.75, i.e., if the volume of the storage tank is reduced to two thirds.

It is worth noting that even though higher μ values result in a faster system response, there will be a minimum allowable storage volume for a range of ambient weather condition. This minimum storage volume depends on several parameters which cannot be selected arbitrarily. The operating condition of the system, including inlet air conditions, has a significant impact on the appropriate size of the storage volume. In practice, the operating condition may change on a daily or even an hourly basis. This suggests that the appropriate liquid desiccant storage volume must be chosen to cover a range of humidity conditions from dry to humid during which the desiccant volume will change significantly. To determine this range of desiccant volumes, the appropriate desiccant type and concentrations must first be chosen. It should be mentioned that the storage volume of the piping is included in μ and therefore μ will decrease as the distance between the supply and exhaust exchangers increases.

3.4. Effect of heat loss or gain (σ)

As presented in Part I of this paper, both heat losses from the salt solution (shown with a (−) value for σ) and heat gains to the liquid desiccant (shown with a (+) value for σ) have a significant effect on both the supply and exhaust sensible and latent effectiveness values of a practical RAMEE system. In this paper, the effect of heat loss/gain during summer and winter operating conditions is studied for a wide range of heat losses/gains and compared to the case where the system is perfectly insulated.

Fig. 6 demonstrates that in the presence of heat loss/gain, the transient response of the system at AHRI summer operating conditions is similar to the case where $\sigma = 0$; however, the quasi-steady effectiveness values on both sides of the RAMEE system change as σ changes. The effect is similar for AHRI winter operating conditions and is not shown graphically.

During summer operating condition, the temperature of the liquid desiccant is higher than its surrounding temperature if the

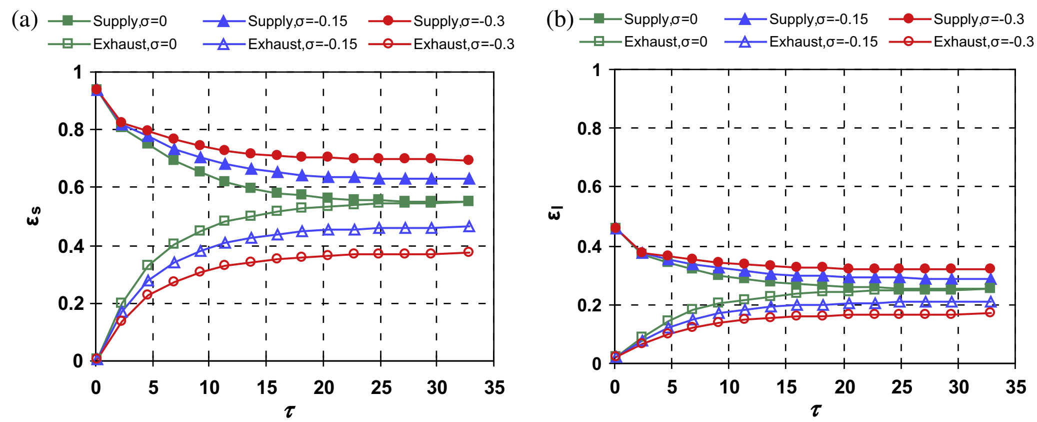

Fig. 6. Transient (a) sensible and (b) latent effectivenesses of the RAMEE system due to heat loss for AHRI summer operating conditions (NTU = 5, $C_{Sol}/C_{Air} = 3$, $\mu = 0.15$, and $\Delta C_{Salt} = 0$).

RAMEE system is housed in a mechanical room which is conditioned close to room temperature. This may result in a heat loss ($\sigma < 0$) from the RAMEE system to the surroundings. Fig. 6 shows that the supply side effectiveness increases as the heat loss increases. In the presence of heat loss from the salt solution, the liquid desiccant temperature will drop and provide higher potential to exchange heat between the warm supply air and the salt solution flow as seen in Fig. 7. Fig. 7 shows that the temperature difference between supply airstream and the salt solution inlet flow ($T_{Air,in,S} - T_{Sol,in,S}$) is higher when there is a heat loss ($\sigma_S = -0.3$) from the system compared to the case of no heat loss ($\sigma_S = 0$). As well, the lower desiccant temperature at a certain concentration ($C_{Salt} = 31.5\%$ corresponds to $\Delta C_{Salt} = 0$ for AHRI summer operating conditions) causes a decrease in the equilibrium humidity ratio of the solution as depicted in psychrometric chart in Fig. 7. As it can be seen in Fig. 7, the difference between the humidity ratio of supply air stream and the equilibrium humidity ratio of salt solution ($W_{Air,in,S} - W_{Sol,in,S}$) increases due to heat loss from the liquid desiccant. Hence, the moisture transfer will enhance in the supply side due to the higher moisture content difference between humid air and the liquid desiccant. This results in an increase in the latent effectiveness of the supply side.

Fig. 8 reveals changes in the effectiveness values on each side of the RAMEE system in the presence of heat loss/gain. From Fig. 8(a) it can be seen that during summer operation an increase in the sensible effectiveness of up to 15% occurs and an increase of up to 7% occurs in the latent effectiveness for the supply exchanger when $\sigma_S = \sigma_E = -0.3$ compared to the case where $\sigma_S = \sigma_E = 0$. For the exhaust side, heat and moisture transfer potential will reduce and result in reduced effectiveness values due to a lower liquid desiccant temperature in the exhaust side of the run-around system. As seen in Fig. 8(a), significant reduction up to 18% occurs in the sensible effectiveness of the exhaust side where $\sigma_S = \sigma_E = -0.3$. Also, the simulation result shows that the latent effectiveness decreases by up to 8% for the same heat loss value. Contrary to summer operating condition, heat loss from the circulated flow during winter operation causes an increase in the exhaust effectiveness values as shown in Fig. 8(b).

3.5. Effect of initial salt solution concentration (ΔC_{Salt})

In practical situations, the RAMEE system may operate with an initial liquid desiccant concentration that can be different than the quasi-steady concentration value. If the initial concentration is dif-

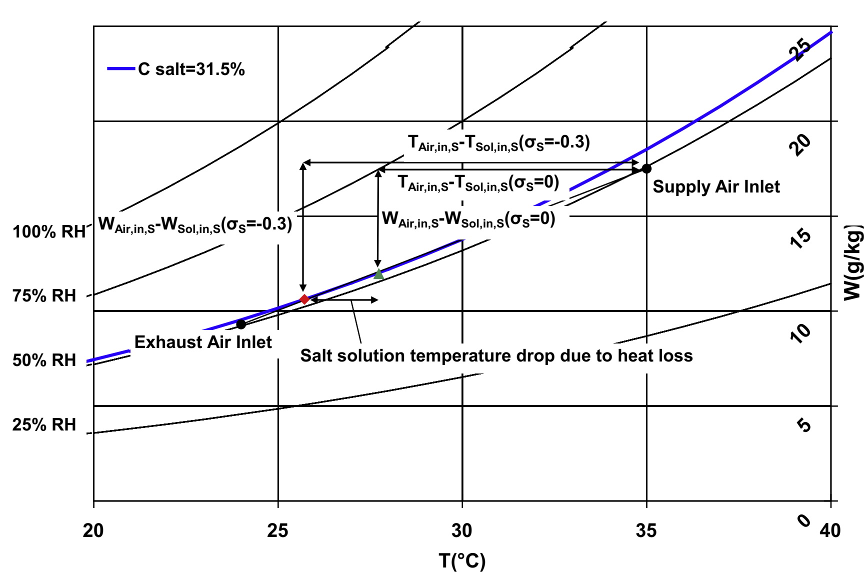

Fig. 7. Change in the heat and moisture transfer potential in the supply exchanger of the RAMEE system due to heat loss effect for AHRI summer operating conditions (NTU = 5, $C_{Sol}/C_{Air} = 3$, $\mu = 0.15$, and $\Delta C_{Salt} = 0$, $\sigma_S = \sigma_E = -0.3$).

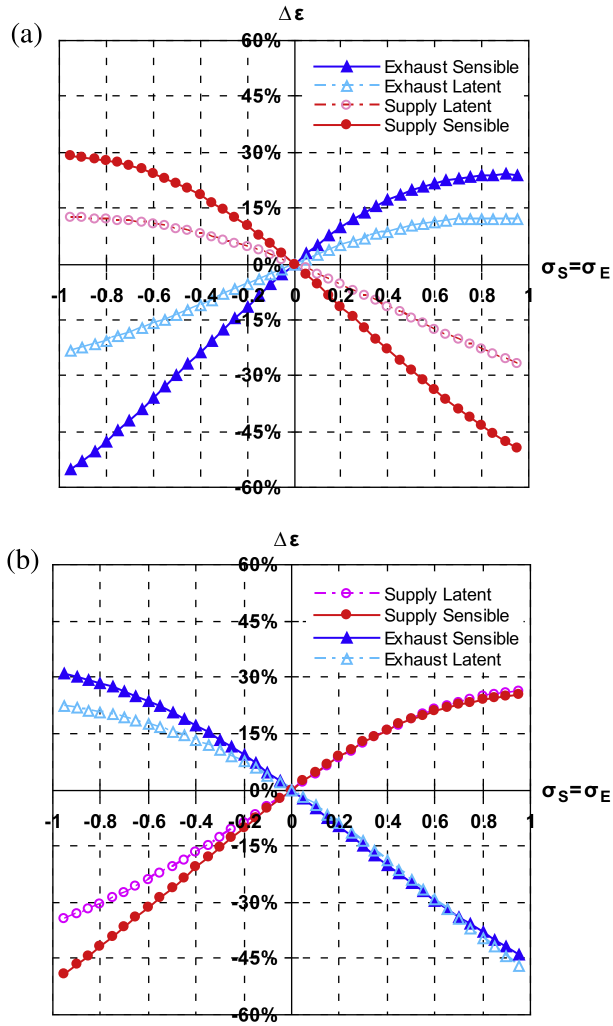

Fig. 8. Change in sensible and latent effectivenesses of the RAMEE system due to heat loss/gain for (a) AHRI summer and (b) AHRI winter operating conditions (NTU = 5, $C_{Sol}/C_{Air} = 3$, $\mu = 0.15$, $\Delta C_{Salt} = 0$).

ferent than the quasi-steady concentration value, the moisture transfer rate in each LAMEE will be different until the liquid desiccant reaches its equilibrium concentration. For instance, if the concentration is initially too high during summer operating conditions, more moisture will be transferred from the supply air to the desiccant in the supply exchanger than will be rejected in the exhaust exchanger. Over time, the concentration of the liquid desiccant will decrease until the moisture accumulated in the supply exchanger equals the moisture rejected in the exhaust exchanger. The RAMEE system may require a long time to reach this quasi-steady state. To study this effect one of the most likely cases will be considered in the following.

As the conditions of the inlet air change over each day, the conditions of the desiccant salt solution also change in order to approach equilibrium. When the salt solution is exposed to indoor conditions during the system shut-down time, which is the same as the exhaust air flow for a sufficient amount of time, it may reach an equilibrium concentration at the indoor exhaust temperature and humidity ratio. This condition indicates $\Delta C_{Salt} = 0.5\%$ at AHRI summer condition and $\Delta C_{Salt} = 7.6\%$ at the AHRI winter condition.

Fig. 9 shows the changes in the dynamic behavior of the RAMEE with this initial equilibrium concentration for the AHRI summer and winter operating conditions. The transient effectiveness values are simulated and compared with the case of $\Delta C_{Salt} = 0$. As seen in Fig. 9(a) and (b), the change in the initial concentration of the liquid desiccant has a trivial influence on the system effectiveness at the AHRI summer conditions. This is caused by the fact that the salt solution concentration remains nearly constant during the AHRI summer operating conditions. The small difference between initial salt solution concentration and its steady state value results in negligible changes in the effectiveness values. These changes are considerably smaller than the uncertainties associated with determining the effectiveness of the run-around system.

In contrast to Fig. 9(a) and (b), Fig. 9(c) and (d) show a substantial impact on the transient effectiveness values as a result of using the liquid desiccant concentration associated with the indoor (exhaust) condition as an initial value at AHRI winter operating conditions. From these figures, it is clear that the system and liquid desiccant have not reached quasi-steady state during the period of simulation with its new selected initial concentration ($\Delta C_{Salt} = 7.6\%$). At the same number of liquid desiccant circulations ($\tau = 40$), Fig. 9(c) demonstrates an 8% increase in the sensible effectiveness of the supply exchanger while the exhaust exchanger sensible effectiveness is reduced by 7% where $\Delta C_{Salt} = 7.6\%$. As seen in Fig. 9(d) the latent effectiveness of the supply side crosses over the exhaust latent effectiveness curve at $\tau = 4.6$. At the end of the simulation, the supply latent effectiveness is reduced by up to 16% compared to the case with $\Delta C_{Salt} = 0$ at $\tau = 40$. This reduction in water vapor transfer or latent effectiveness may be a disadvantage at this operating condition but it should be noted that the supply air will be humidified during the entire transient period, which may be a very desirable result even if it is small. Contrary trends for the latent effectiveness of the exhaust exchanger are obtained, as an increase of up to 16% is found compared to the predicted value where $\Delta C_{Salt} = 0$. Again this implies more water vapor is added to the liquid salt solution in the exhaust exchanger than is removed in the supply exchanger. This phenomenon is expected, since the liquid desiccant moves toward its equilibrium concentration which is 7.6% lower than its initial concentration.

The reason for these observed behaviors in Fig. 9(c) and (d) is mainly attributed to the operating concentration of the salt solution in the system, which results in different equilibrium humidity ratio values. During the winter operating condition discussed above, the higher concentration results in a lower humidity ratio for air in equilibrium with the liquid desiccant as illustrated in psychrometric chart (see Fig. 4 in Part I). This reduction results in a higher moisture transfer rate on the exhaust side of the exchanger compared to the moisture transfer rate at steady state concentration because the driving potential for moisture transfer is higher. Therefore, more water is transferred from the humid exhaust air to the desiccant during the transient period. Similarly, the moisture transfer rate in the supply side decreases because the driving potential for moisture transfer is lower due to the high salt concentration compared to equilibrium concentration. Consequently, the latent effectiveness values are higher on the exhaust side and lower on the supply side during the transient period as compared to the case where $\Delta C_{Salt} = 0$ as shown in Fig. 9(d).

Fig. 9(c) shows that the sensible effectiveness is higher on the supply side when $\Delta C_{Salt} = 7.6$ than when $\Delta C_{Salt} = 0$. These higher sensible effectiveness values are due to the lower moisture transfer rate from the liquid desiccant to the air in the supply side when $\Delta C_{Salt} = 7.6$ than when $\Delta C_{Salt} = 0$. The lower moisture transfer rate reduces the cooling of the liquid by the evaporation phase change and thus the liquid desiccant temperature is higher when $\Delta C_{Salt} = 7.6$. This increases the temperature difference between two fluids in the supply side for the case of $\Delta C_{Salt} = 7.6$ which causes more heat to transfer from the liquid desiccant to the air. This results in an increase in the sensible effectiveness on the supply side when $\Delta C_{Salt} = 7.6$ compared to when $\Delta C_{Salt} = 0$. These results reveals that the complex nature of the RAMEE system

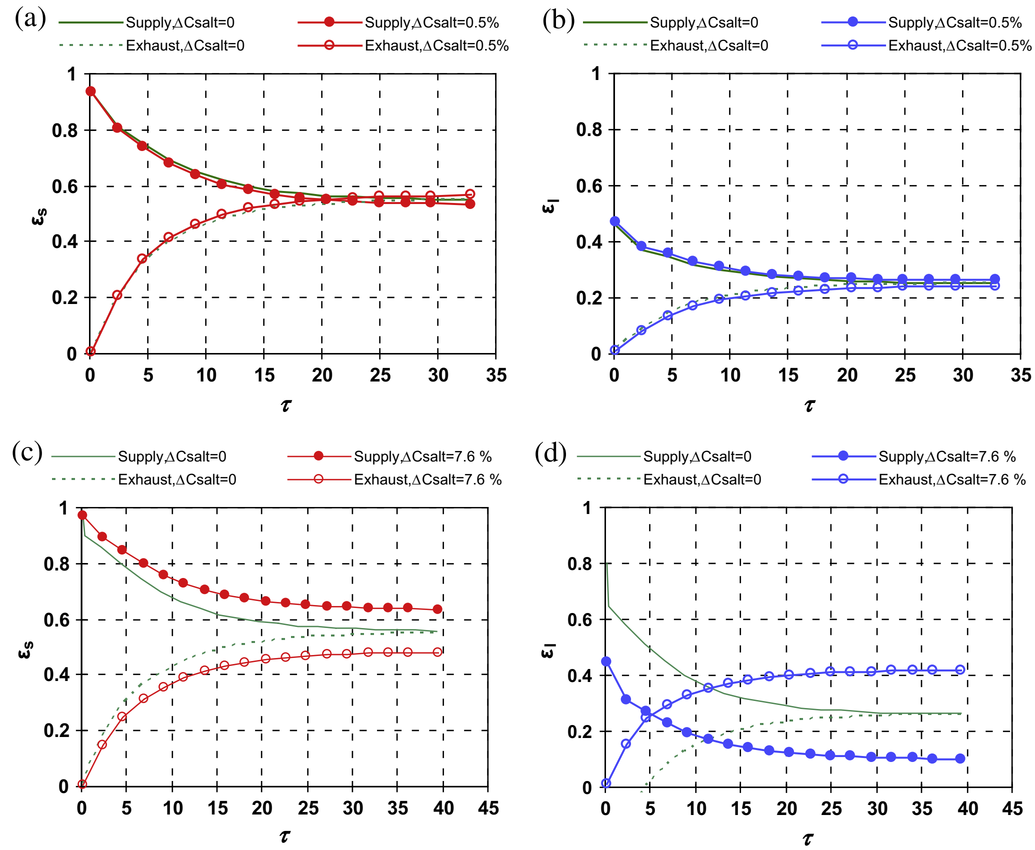

Fig. 9. System effectivenesses versus dimensionless time for AHRI summer condition with $\Delta C_{Salt} = 0.5\%$, (a) sensible and (b) latent and AHRI winter condition with $\Delta C_{Salt} = 7.6\%$, (c) sensible and (d) latent (NTU = 5, $C_{Sol}/C_{Air} = 3$, $\mu = 0.15$, $\sigma = 0$, $0 < \tau < 40$).

which means that many parameters and operating conditions must be considered if one is to understand the reason for change in the system effectiveness for the supply and exhaust side exchangers.

Fig. 9(c) and (d) show that when $\Delta C_{Salt} \neq 0$, the supply and exhaust effectivenesses change very slowly for $\tau > 30$. The simulations were continued for longer time periods as shown in Fig. 10 and the results show that the liquid desiccant concentration continues to change gradually with increasing time. However, this change is very slow and the system requires a significant number of desiccant circulations to satisfy both conservation of energy and mass criteria for the air streams.

In addition to the numerical model results, similar time delays ($t > 5$ h) were observed in the laboratory test data for the RAMEE system (see Part I). Thus, a different convergence criterion is defined to identify the large transient response time of the RAMEE system for the case where $\Delta C_{Salt} \neq 0$. As illustrated previously in Part I, this convergence criterion ($|\partial\varepsilon/\partial\tau| \leqslant 5 \times 10^{-6}$) considers only the rate of change in the effectiveness values during the transient period as the salt solution approaches its equilibrium value for each operating condition. When this rate changes very slowly, the system is considered to be in quasi-steady state conditions. Fig. 11 shows the effect of the using different initial salt solution

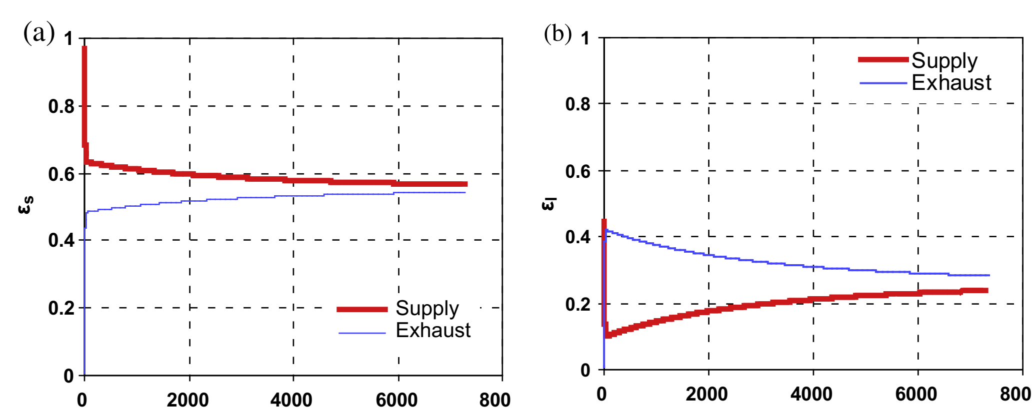

Fig. 10. System effectiveness versus dimensionless time for AHRI winter condition with $\Delta C_{Salt} = 0.5\%$, (a) sensible and (b) latent (NTU = 5, $C_{Sol}/C_{Air} = 3$, $\mu = 0.15$, $\sigma = 0$, $0 < \tau < 7281$).

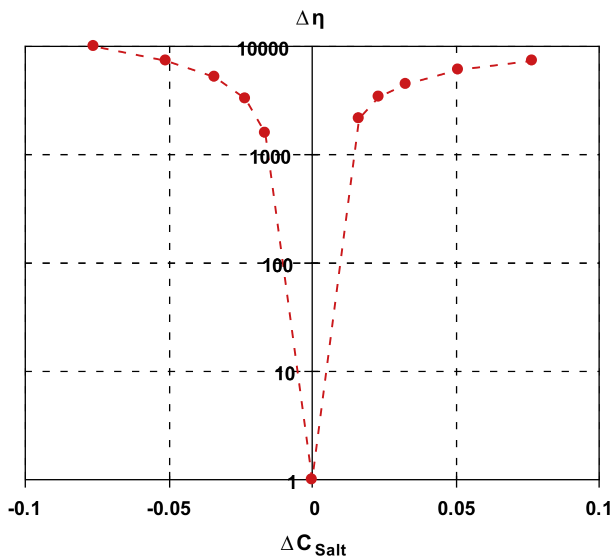

Fig. 11. Change in the number of liquid desiccant circulations ($\Delta\eta$) to the reach quasi-steady state ($|\partial\varepsilon/\partial\tau| \leqslant 5 \times 10^{-6}$) for the RAMEE system due to different initial concentrations that differ from equilibrium (NTU = 5, $C_{Sol}/C_{Air} = 3$, $\mu = 0.15$, $\sigma = 0$, AHRI winter conditions, $\Delta\eta = \eta(\Delta C_{Salt} = 7.6\%) - \eta(\Delta C_{Salt} = 0)$).

concentrations on the transient response of the RAMEE system, applying aforementioned convergence criterion for AHRI winter operation conditions. This figure shows that non-equilibrium initial salt solution concentrations dramatically increase the time to reach quasi-steady state condition.

As illustrated in Fig. 11, a difference of around 8% between the initial salt solution concentration and its expected steady sate value results in the liquid desiccant having to travel through about ten thousand more circulations through the system before the steady state concentration is attained. For the specific RAMEE system parameters of Table 2 in Part I and operating conditions of Fig. 11, this number of circulations represents a month in real time, which indicates that the system would require almost a month to reach equilibrium. This clearly shows the importance of choosing a salt solution concentration value close to its steady state value for the specific climate being considered to avoid large time delays to reach equilibrium in practical applications of the RAMEE system. In additions, some system control procedures such as adding water or heat to the liquid desiccant loop could be used during the operation of the system to move the system toward equilibrium more quickly. This will be the topic of future studies.

4. Conclusions

Using the model developed in Part I of this paper, the transient effectiveness of the RAMEE system is investigated for AHRI test conditions following a step change in the supply air inlet temperature and humidity ratio. The system transient behavior is analyzed showing the effect of several dimensionless parameters. It is shown that the storage volume of liquid desiccant salt solution has a significant impact on the transient response of the system, implying that the size of the storage tank should be minimized considering the range of operating conditions and the design constraints. It is also shown that the presence of heat loss/gain to/from the surroundings changes the quasi-steady state effectiveness values significantly, but has negligible effect on the transient response times. It is shown that the initial salt solution concentration has the greatest effect on the transient response time of the system. To reduce this transient response time during the operation of the RAMEE system, the salt solution concentration should be chosen to be very close to the steady state value that will exist for the specific climate being considered, or in a practical application, it should be controlled.

Acknowledgements

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