

2010

Transient Lumped Parameter Modeling For Vapour Compression Cycle Based Refrigerator

Chetan Tulapurkar
General Electric

Richa Khandelwal
General Electric

Follow this and additional works at: <http://docs.lib.purdue.edu/iracc>

Tulapurkar, Chetan and Khandelwal, Richa, "Transient Lumped Parameter Modeling For Vapour Compression Cycle Based Refrigerator" (2010). *International Refrigeration and Air Conditioning Conference*. Paper 1129.
<http://docs.lib.purdue.edu/iracc/1129>

This document has been made available through Purdue e-Pubs, a service of the Purdue University Libraries. Please contact epubs@purdue.edu for additional information.

Complete proceedings may be acquired in print and on CD-ROM directly from the Ray W. Herrick Laboratories at <https://engineering.purdue.edu/Herrick/Events/orderlit.html>

Transient Lumped Parameter Modeling For Vapour Compression Cycle Based Refrigerator

Chetan TULAPURKAR^{1*}, Richa KHANDELWAL²

¹GE India Technology Centre, GE Global Research,
Bangalore, Karnataka, India
+91 80 4088 2218, +91 80 2841 2111, chetan.tulapurkar@ge.com

²GE India Technology Centre, GE Global Research,
Bangalore, Karnataka, India
+91 80 4088 1425, +91 80 2841 2111, richa.khandelwal@ge.com

* Corresponding Author

ABSTRACT

Owing to the various regulatory norms, reduction in refrigerator energy consumption has been subjected to a lot of research. When modifying any design to achieve this objective, experiments are usually performed for performance prediction/ assessment, which are expensive and time consuming. Hence to minimize the number of experiments, it is essential to establish a method to predict the performance numerically. Refrigerator, during start-up goes through an initial pull down cycle i.e. temperature of the refrigerator compartments decreases to a required operational point. After that, the refrigerator goes through continuous compressor on-off cycles due to heat leakage through walls and gaskets. It has always been a challenge to model refrigerator operations numerically due to its transient nature. In the present work, a methodology to predict this transient behavior of a domestic refrigerator has been developed and discussed. The methodology embraces the development of transient model based on lumped parameter method, which predicts evaporator temperature, interaction of sealed system with in-compartment air and compartment temperature. This model is robust and computationally very economical, bringing down the design cycle time significantly. This model is intended for qualitative predictions and provides a strong foundation towards developing it further for more accurate quantitative predictions.

1. INTRODUCTION

Refrigerator operation, in practice, can be characterized into steady state and transient. In the steady state, the input and output parameters are constant over time. The transient operation can be characterized by a start-up or a shutdown, or any deviation from steady state, caused by either external changes in conditions such as load, ambient temperatures, or by feedback control. In either case, the system attempts to move from one equilibrium state to another. Transient modeling is the predictive analysis of the system's operation during such conditions. Prediction of transient behavior is important to simulate major performance parameters such as temperature uniformity in the freezer and fresh food compartments (maximum allowable tolerance of 6 °F) and energy consumption. Very often these performance parameters are obtained from experimental tests, which need experimental set-up, considerable testing time and multiple trials. Moreover, the experimental effort further increases the process of design optimization including significant cost involvements. Hence there has been a need for predicting the refrigerator performance through flow and thermal modeling.

Refrigerator components may be modeled either from a known map (for compressor) of its performance or from basic engineering principles (for heat exchangers). For heat exchangers, a sub-classification of modeling techniques is the phase-dependent moving boundary method and the phase-independent finite difference methods. Another category of modeling techniques consists of a lumped versus distributed parameter method. The lumped parameter method averages the state parameters over the complete control volume, and results in a set of algebraic and first order ordinary differential equations to render computationally simpler models. The distributed method predicts

spatial variations and the typical modeling approach is Computational Fluid Dynamics (CFD). Since CFD takes more time and effort, lumped parameter method is often used, which is easier and faster way to simulate the model. Efforts have been made in past to model transient behavior of such vapor compression system and study various aspects of the system using lumped parameter method. Bendapudi and Braun (2002) carried out detailed review of published literature on transient models of vapor compression system. This article reviewed the work of Wedekind *et al.* (1978), Dhar and Soedel (1979), Goldschmidt and Hart (1982), Sami *et al.* (1987), Vargas and Parise (1995) and several other studies on transient development of refrigerator components. Wedekind *et al.* (1978) were among the earliest to develop the transient behavior with their work on modeling of two phase-flow dynamics in heat exchangers. Dhar and Soedel (1979) developed model for a complete vapor compression refrigeration system capturing all the major transients by implementing first principles approach and using a moving boundary approach in the heat exchangers. Goldschmidt and Hart (1982) developed a lumped model for a refrigeration system with a focus on studying its seasonal performance when coupled to a mobile home whose heat losses were modeled in detail. Sami *et al.* (1987) also used lumped parameter approach to model the system components where the dynamics were relevant. Literature also revealed Vargas & Parise (1995), Xiandong He *et al.* (1997) and Williatzen *et al.* (1998) using lumped parameter approach to study the effect of various refrigerator components. Rossi & Braun (1999) presented the importance of real time simulation for a roof top air conditioning unit. They simulated start-up and on-off cycling of this system. Hermes and Malo (2006) developed a first principle model for simulating the transient behavior of household refrigerators and validated energy consumption of the system. Cai *et al.* (2006) developed a 1D heat transfer model of the foodstuff present in the cabinet studying the sensitivity of certain type of food to surrounding temperature. Steady state models have also been developed in the past to predict the energy consumption of household refrigerator e.g. Goncalves *et al.* (2008).

As evident from the literature review, most of literature consists of significant work on vapor compression system models. There is limited work on transient models of complete refrigerator, which is the major commercial refrigeration equipment in use. In the present work, a methodology has been developed for predicting transient behavior of refrigerator through computational models, which reduces overall design cycle time from one year to one week for initial estimation. Further a user-friendly graphical user interface (GUI) has also been developed. This model could serve as a foundation for predicting key system performance parameters such as annual energy consumption and cycle time.

2. MATHEMATICAL FORMULATION

In the present work, a vapor compression system based refrigerator is considered. The development focuses on the evaporator and compartments of the system, modeling the effect of compressor with the compressor map. The evaporator is modeled based on Net Transfer Units (NTU) approach, with refrigerant and air as two fluid streams. This model is developed for the purpose of predicting annual energy consumption over a time period, which may include initial pull-down or cycling on/off or both, focusing on identifying compartments' temperature, humidity, and also as an aid to the system designer in determining optimal performance. Based on this model, a simulation program has been developed in MS Excel with Visual Basic Macro. Further, a user-friendly graphical user interface (GUI) has been developed in Visual Basic .NET.

2.1 Refrigerant and air properties

Refrigerant properties are obtained from NIST REFPROP database. This is an MS Excel add-in. This module can be used in the MS Excel worksheet for calculating the refrigerant properties. The software also comes with the front-end for calculating and plotting properties. The database provides various thermo-physical properties of relevant substances e.g. R-134a, R-600a, air.

2.2 Refrigerant-air model

A schematic of a typical sealed system, compartments and airflow has been shown in Figure 1. The sealed system components such as compressor, condenser, capillary tube and evaporator have been presented in Figure 1(a), whereas the airflow path has been shown in Figure 1(b).

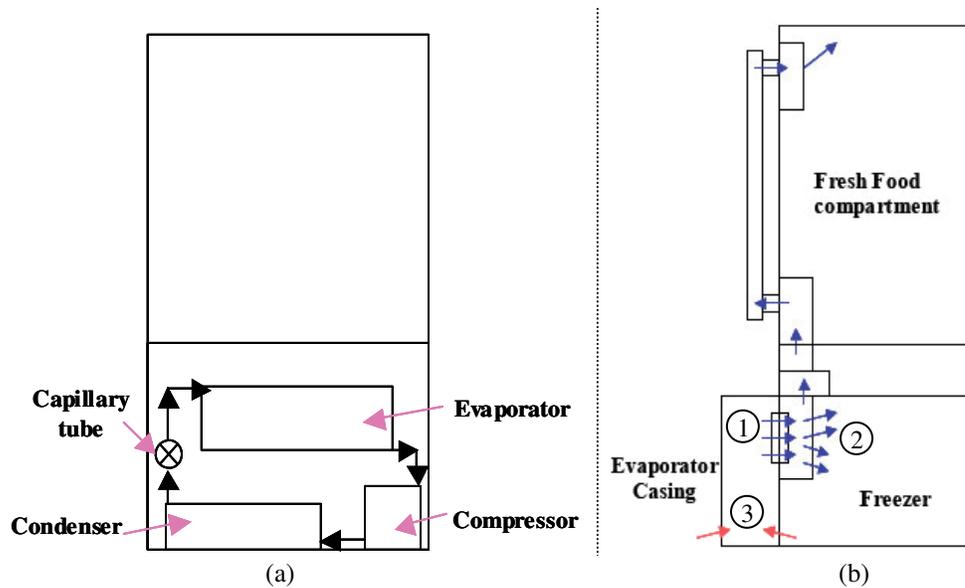


Figure 1: (a). Back-view (b). Side-view of a bottom-mount refrigerator

The figure highlights airflow in section 1 (before evaporator), section 2 (after evaporator) and section 3 (fresh food and freezer airflow mixing section). The mixing of air streams occurs between section 1 and section 3. Present refrigerant-air model is applicable between section 1 and section 2. The model is based on NTU design approach of heat exchanger, and it predicts air temperature and refrigerant temperature over time. The inputs for this model are inlet air temperature, air humidity and NTU of evaporator. The list of input parameter is given in Table 1.

Table 1: Input parameters for evaporator-air model

Parameter	Unit	Typical value
Evaporator air model inputs:		
Air inlet temperature (T_1)	K	295
Air inlet humidity (ω_1)	g/kg dry air	18
NTU of evaporator (NTU)	--	0.85
Compressor map	--	--
Open heat exchanger model inputs:		
Exiting compartment temperature (T)	K	296
Existing compartment humidity (ω)	g/kg dry air	18.1
Leakage air temperature	K	300
Leakage air humidity	g/kg dry air	18.1

Compressor map can be obtained from the compressor manufacturer. As discussed, the air exit temperature (T_2) is calculated from NTU approach as presented by the following equation:

$$\frac{T_1 - T_2}{T_1 - T_e} = 1 - \exp(-NTU) \quad (1)$$

Where T_1 is inlet air temperature, T_2 is outlet air temperature, T_e is evaporator temperature and NTU can also be calculated from following equation:

$$NTU = \frac{UA}{c_{\min}} \quad (2)$$

Where U is overall heat transfer coefficient from refrigerant to air, A is evaporator surface area for heat transfer and c_{\min} is the minimum heat capacity rate (product of mass flow rate \dot{m} and specific heat C) of the two streams; refrigerant and air streams.

The air exit humidity (ω_2) is calculated from NTU approach using

$$\frac{\omega_1 - \omega_2}{\omega_1 - \omega_{\text{air}, T_e}} = 1 - \exp(-NTU) \quad (3)$$

Where ω_1 is inlet air humidity, ω_2 is outlet air humidity and ω_{air, T_e} is the saturated humidity of air at evaporator temperature.

For present work, NTU of domestic refrigerator is considered 0.85 based on the experiments carried out in a different work scope. Then assuming a random refrigerant evaporator temperature (T_e) value (between -50°C to 50°C), air exit temperature (T_2) is calculated from Equation 1. Similarly, air exit humidity value (ω_2) can be obtained. For the assumed evaporator temperature (T_e), evaporating capacity of compressor is calculated from the compressor map. For the presented model, compressor work (W_e) is expressed as in equation 4.

$$W_e = 0.29(1412.2 + 27.8T_e - 3.58T_e^2 + 0.2329T_e^3) \quad (4)$$

Where T_e is evaporator temperature, T_c is condenser temperature and W_e is cooling capacity. For proper energy balance, the heat lost by air should be inline with the NTU equivalent of heat absorbed by the refrigerant. If the calculations show otherwise then it implies that the assumed refrigerant temperature is not correct and hence a different refrigerant temperature has to be assumed. It is an iterative process, where refrigerant temperature is assumed (between temperature range -50°C to 50°C in the step of 0.5°C). The refrigerant temperature, for which heat gained by refrigerant and heat lost by air are inline with NTU methodology, would be the correct converged temperature for a given set of input values. An algorithm has been developed using this concept and further a simulation program has been developed based on this algorithm. Figure 2 below shows the algorithm.

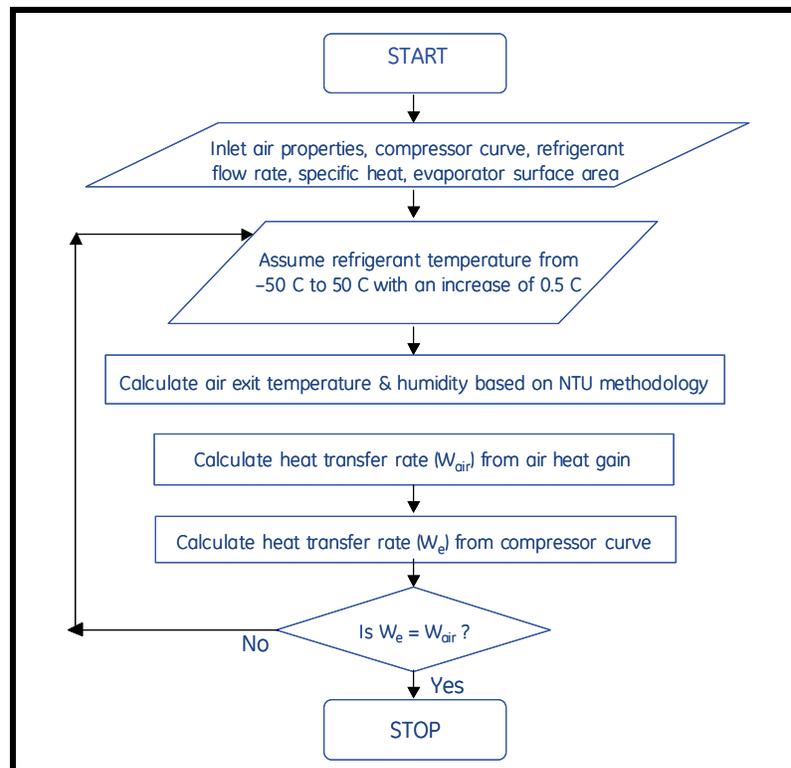


Figure 2: Algorithm for calculating refrigerant temperature & air properties at evaporator exit

2.3 Compartment model

In the previous section, refrigerant-air model has been discussed, which is applicable between section 1 and 2 (before and after evaporator), as shown in Figure 1(b). In this section, compartment model is discussed, which is applicable between section 2 and section 3. The model is based on laws of energy and mass conservation. When air stream flows from evaporator surface to the compartment, the stream gains heat due to compartment load and heat leakage from ambient to the compartment. Moreover, inlet cold air stream changes the average temperature of the compartment. Similarly humidity of air changes due to the air leakage from ambient to the compartment and incoming air stream from evaporator. The inputs for this model are inlet air properties, refrigerant flow properties, evaporator surface area and heat transfer coefficient. The input parameters have already been presented in Table 1.

The temperature (T') of the compartment for a future time step is calculated from the air inlet and exit humidity, airflow rate, heat leakage from the ambient to the compartment, heat capacity and current time step temperature of the compartment.

$$\dot{m}_{air}(h_2 - h_3)dt = MC_p(T - T') + W_l dt \quad (5)$$

Where T is the initial temperature, which is defined by the user and has been assumed to be the room temperature for current study. T' is the temperature after the time step dt , h_2 and h_3 are the enthalpy of air at section 2 and 3 respectively. MC_p is the heat capacity of the compartment, which can be calculated from the compressor OFF time (t_{OFF} : duration for which compressor was switched off), heat leakage rate to the compartment and temperature range of the compartment. W_l is the heat leakage rate from ambient to the compartment. The equation for determining MC_p is as below:

$$MC_p(T_{max} - T_{min}) = W_l t_{OFF} \quad (6)$$

where T_{max} and T_{min} are the maximum and minimum compartment air temperature between compressor on/off and t_{OFF} is the time duration when the compressor is switched off. In equation 5, the effect of air leakage from ambient into the compartment has been assumed negligible. The expression for the air humidity for the next time step is given below

$$\omega' = (\dot{m}_{air}(\omega_2 - \omega)dt + \omega \rho_{air} V + \dot{m}_l \omega_l dt) / (\rho_{air} V) \quad (7)$$

Where ω' is the humidity of the compartment for the next time step calculated from the inlet (ω_l) and exit (ω_2) humidity, air leakage mass flow rate (\dot{m}_l), compartment air mass flow rate (\dot{m}_{air}), current time step humidity (ω) of the compartment, volume of the compartment (V) and density of the air inside the compartment (ρ_{air}). From the existing experimental data, heat capacities of the compartments are determined from Equation 6. The airflow from section 2 (after evaporator) is distributed into two streams: fresh food and freezer compartment streams. The mass flow rate of these streams can be obtained from the refrigerator manufacturer. For the present work, assumed fresh food airflow rate is 5 cfm and freezer airflow rate is 25 cfm. Using equation 5 and equation 7, the temperature and humidity of compartment in the future time step is calculated. Thus, using this methodology, transient phenomenon of a refrigerator can be numerically captured.

3. RESULTS AND DISCUSSIONS

In the developed lumped parameter model, a vapor compression cycle based domestic refrigerator has been considered. Here it is very important to note that the developed model is a foundation towards a complete predictive tool for domestic refrigerator. For example in actual refrigerator, the control system involves actuation of compressor, damper and fan, based on average temperatures of freezer and fresh food compartments. However, in this model, the freezer temperature has been assumed to be the only parameter to control compressor ON/ OFF. The model can be extended to take in to account actual control procedures, which was not within the scope of the present work.

The typical values of input parameters have been presented in Table 2. The input parameters include refrigerant type, ambient temperature, compartment temperature range, initial temperature of the compartments etc.

Table 2: Inputs for the presented results

Parameter	Value	Unit	Parameter	Value	Unit
Type of refrigerant	R134a	N/A	Initial inlet air temperature	27	°C
Ambient temperature	27	°C	Initial inlet air humidity	18	g/kg
Ambient pressure	1.013	bar_a	Condenser temperature	45	°C
Ambient humidity	18	g/kg	Condenser pressure	11.2	bar_a
Evaporator temperature	-30	°C	FZ initial temperature	27	°C
Evaporator pressure	0.77	bar_a	FZ initial humidity	18	g/kg
FF initial temperature	27	g/kg	FZ minimum temperature	-16	°C
FF initial humidity	18	g/kg	FZ maximum temperature	-11	°C
FF minimum temperature	0	°C	FZ leakage mass flow rate	1e-06	kg/s
FF maximum temperature	5	°C	Time step	1	sec
FF leakage mass flow rate	1e-06	kg/s	Real time duration	30000	sec

The compressor state is controlled by the freezer temperature, which varies between the given ranges of freezer compartment temperature as shown in Figure 3.

The model predicts temperatures of refrigerant in evaporator, evaporator wall, evaporator casing, freezer air, fresh food air, and food inside compartments. For the inputs shown in Table 2, the output has been shown in Figure 3 below.

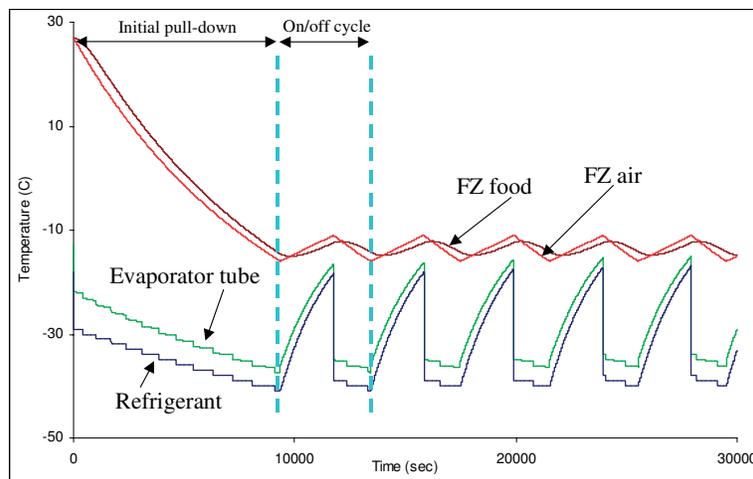


Figure 3: Initial pull-down and compressor on/off cycling process

Figure 3 shows four temperatures (refrigerant, evaporator tube wall, freezer air and food in freezer) and two states (initial pull-down and on/off cycle). Initial pull-down state starts from ambient temperature and ends when the freezer temperature approaches the specified minimum temperature (-16 °C) and the compressor is then switched off. After this the temperature in the freezer starts to increase till it reaches maximum specified temperature (-11 °C) and then the compressor is switched on again. This causes cycling of compressor on/off as seen in Figure 3. The model also predicts evaporator casing and fresh food compartment temperatures and is presented in Figure 4.

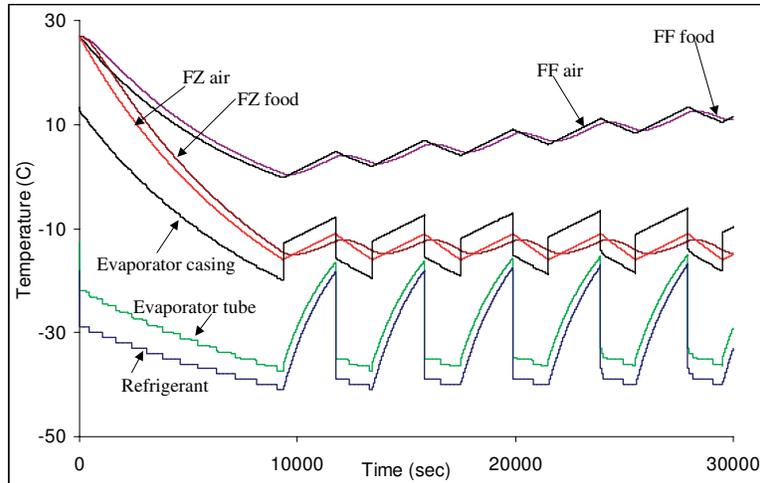


Figure 4: Transient temperature profile from developed model

The temperature of air and food in fresh food compartment are observed to be increasing during the cycling period. This is because it has been assumed in the model that the compressor on/ off is controlled based on the freezer temperature only. The control of the fresh food compartment will be added in future work and is not covered in present work scope. In practice, the compressor on/off is controlled based on freezer and fresh food temperature together and hence both the compartment temperatures are maintained within a specified range. These temperature profiles are useful in determining compressor on and off time duration, which can be used to calculate the energy consumption. Compressor off time was observed to be 1.5 times the compressor on time. Humidity prediction is not included in the present work.

4.CONCLUSIONS

In the present work, a methodology has been developed to model transient behavior of the refrigerator. This would act as foundation to transient model of domestic refrigerator, using lumped transient model. The transient lumped parameter model and simulation program has been developed to capture and predict the following:

- Temperature of compartments (freezer and fresh food) and refrigerant in the evaporator
- Initial compressor pull down
- Compressor on-off cycle based on freezer temperature
- Duration of compressor on and off which will help in predicting the compressor power consumption over time

This methodology, based on lumped parameter model, will reduce the overall cycle time in predicting the transient compartment temperatures and will also decrease the experimental effort. These models are useful for qualitative results and can provide a strong foundation towards developing them further for quantitative prediction. Though the temperature profile and compressor on/off time duration is inline with the actual numbers, detailed validation is required.

NOMENCLATURE

A	surface area	(m ²)	Subscripts	
c	heat capacity rate	(W/K)	1	section 1
C	specific heat	(J/kg K)	2	section 2
dt	time	(sec)	3	at Section 3
h	enthalpy	(kJ/kg)	air	related to air
\dot{m}	mass flow rate of the fluid	(kg/s)	c	condenser
MC _p	heat capacity	(J/K)	e	evaporator
NTU	number of transfer units	(-)	l	air leakage from ambient into compartment
T'	temperature in next time step	(K)	max	maximum
U	overall heat transfer coefficient	(W/m ² K)	min	minimum
V	compartment volume	(m ³)	OFF	compressor OFF mode
W	heat flow rate	(W)	p	pressure
ρ	density	(kg/m ³)	Abbreviations	
ω	absolute humidity	(g/kg)	1D	1 dimensional
ω'	absolute humidity at next time step	(g/kg)	cfm	mass flow rate in cubic feet per minute
			FF	fresh food compartment
			FZ	freezer compartment

REFERENCES

- Bendapudi, S., Braun, J. E., 2002, A Review of Literature on Dynamic Models of Vapor Compression Equipment; *ASHRAE Report # 4036-5*.
- Cai Junping, Raisum Jorgen, Thybo Claus, 2006, "Dynamic Heat Transfer Model of Refrigerated Foodstuff", *International Refrigeration and Air Conditioning Conference*, Purdue, R042.
- Dhar M. & Soedel W., 1979, "Transient Analysis of a Vapor Compression Refrigeration System" XV *International Congress of Refrigeration*, Venice.
- Goldschmidt, V.W., Hart, G.H., 1982, "Heat Pump System Performance: Experimental And Theoretical Results", *ASHRAE Transactions* Vol. 88, Part 1, pp. 479-489.
- Gonclaves Joaquim M., Hermes Christian J.L., Melo Claudio, Knabben Fernando T., 2008, "A simplified steady state model for predicting the energy consumption of household refrigerators and freezers", *International Refrigeration and Air Conditioning Conference*, Purdue, 2145.
- Hermes Christian J.L. and Milo Claudio, 2006, "A dynamic simulation model for Fan-and-Damper controlled refrigerators", *International Refrigeration and Air Conditioning Conference*, Purdue, R036.
- Rossi T.M and Braun J.E., 1999, "A real-time transient model for air conditioners", *Proc. 20th International Congress of Refrigeration*, Sydney, Paper No. 743.
- Sami S.M., Duong T., Mercadier Y and Galanis N., 1987, "Prediction of the transient response of heat pumps", *ASHRAE Transactions*, Vol. 93, pp. 471.
- Vargas J.V.C. & Parise J.A.R., 1995, "Simulation In Transient Regime Of A Heat Pump With Closed-Loop And On-Off Control", *International Journal of Refrigeration*, Vol. 18, No. 4, pp. 235-243.
- Wedekind G.L., Bhatt B.L. Beck B.T., 1978, "A system mean void fraction model for predicting various transient phenomena associated with two phase evaporating and condensing flows.", *International Journal of Multiphase Flow*, Vol. 4, pp. 97-114.
- Williatzen M., Petit N.B.O.L. & Ploug-Sorensen L., 1998, "A general dynamic simulation model for evaporators and condenser in refrigeration: Part 1 – moving boundary formulation of two-phase flows with heat exchange", *International Journal of Refrigeration*, Vol. 21, No. 5, pp. 398-403.
- Xiandong He, Sheng Liu & Asada H.H., 1997, "Modeling of vapor compression cycles for multivariable feedback control of HVAC systems", *ASME Journal of Dynamic Systems, Measurement and Control*, Vol. 119, No. 2.