

How Evaporator of Automotive Air Conditioner is Modelled? A Systematic Review

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Abstract: Evaporator is one of essential components for automotive air conditioning system. Evaporator operates between 4–5°C superheat at the refrigerant exit condition with applying a margin of safety to assure that the flow does not be in a liquid phase, while entering the compressor. If the two-phase region gets close to the exit of the evaporator and the system does not have an accumulator, liquid droplets might enter the suction line and harm/damage the compressor. A through area expansion valve indirectly senses the evaporator exit superheat and adjusts the process flow consequently. Understanding evaporator dynamics and the way it works is essential for quality modeling process. The goal of this work is to introduce a review study of evaporator and the principle operation as well as different models presented in the early studies. About eight different evaporator models are reviewed and discussed in details. Such review study has not been introduced, according to the best of the author knowledge.

Keywords: Air conditioner; Automotive; Evaporator; Models; Review.

1. INTRODUCTION

In view of our earlier studies in automotive research via different issues [1–31], and refrigeration/air condition systems [32–34], we study here one important area in automotive research, which is a review study for refrigeration systems, in particular, evaporator. The evaporator is one of main components of automotive air conditioning systems, as shown in Figure 1. Actually, there has been a great deal of theoretical and experimental studies toward developing and understanding evaporator. To evaluate the soundness of evaporator, modelling studies are required to explain the dynamics and instabilities. Many strategies are applied to model evaporator. First, a black-box model uses elements square measure delineated solely by input output relationships. This technique used management theory to characterize stability and perceive feedback needed. However, square measure could not predict the system response in an operative conditions, wherever the transfer functions of the square measure are defined via experimental investigations. As a result, black-box modelling solely uses input-output relationships and this method is difficult to be developed. Additionally, the physics of the system is lost within the analysis. Second, two-zone model that typically uses a lumped-parameter approach. In this model approach, the evaporator is divided into different regions, as two-phase flow and superheat, wherever the conservation equations is applied to every region separately. The two-zone model is typically a computationally cheap and considering physical behavior of evaporator. The two-zone model considers a number of variables in an exceedingly region, like the convection constant and void fraction, for the spatially averaged of analysis. Third, a distributed model that discretizes the evaporator into several tiny zones very similar to a finite-volume Computational Fluid Dynamic (CFD) analysis. The model is more correct than the two-zone model as a result of the ability to predict behavior of proper flow. However, the model is complicated, requiring way more computational time than the two-zone models.

In addition to early models discussed above, a number of previous studies on modelling evaporator was well known within the literature. There are some other modelling approaches for evaporator, such as distributed parameter modelling approach [35], lumped-parameter approach [36] and partial lumped-parameter approach [37], are applied in many studies. It is, however, noted that some previous models showed operative parameters influenced on each other. Park *et al.* [38] solved a steady-state twin evaporator air conditioning system model to investigate the cross coupling effects between two evaporators within the system. He and Asada [39] gift a low-order model for evaporator air conditioning system that consisted of a feedback linearization within the system dynamics. Pan *et al.* [40] presented a modelling tool on the operational performance of evaporator air conditioning. A generalized modelling approach for evaporator air conditioning was planned by Shah *et al.* [41]. The model validation on each evaporator air conditioning system showed desired model responses. Zhu *et al.* [42] reported a model of evaporator air conditioning using TRNSYS simulation code. Two varieties of algorithms were provided and tested to be appropriate for modelling system. Elliott and Rasmussen [43] employed a two-phase fluid network approach. Shao *et al.*

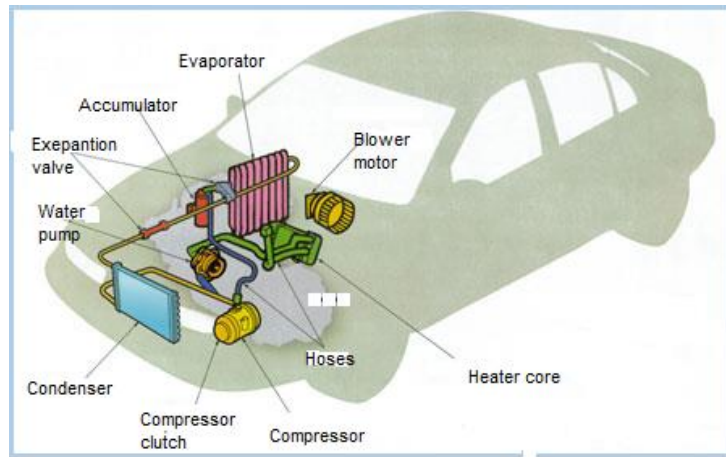


Figure 1. Automotive air conditioning system and detail components

[44] and Shi *et al.* [45] developed a model to predict the performance of various complicated refrigeration systems, including evaporator systems. Chen *et al.* [46] developed a simplified dynamic model using victimization lumped-parameter modelling approach. However, no experimental validation for the model was conducted.

However, there are some other studies associated with modelling of evaporator air conditioning system, which are experimental validation [41–43] or supported system identification [47, 48]. In this study, complete overview of evaporator models is presented and discussed in details.

2. REVIEW OF EVAPORATOR MODEL

2.1 Control Theory Model

He *et al.* [49] developed a mixed lumped-parameter model for evaporator. The model takes into account response of the evaporating pressure, condensation pressure, and superheat change within compressor speed, fan speed, and valve opening conditions. The dynamics of the evaporator and condenser were considered input-output pairs. The model was compared to experimental work. Results found that the model could capture the dynamics of the superheat signal style precisely.

Broersen van der Jagt [50] applied open-loop model for the dynamics of evaporator using single-input/output feedback. The single-input and single-output feedback considers refrigerant mass flow. The author preliminary suggests a decrease of the mass rate with eliminating exit temperature oscillations. The model increased the thermal resistance of the bulb by adding material between the bulb and evaporator. Increasing the resistance poses a tangle throughout start-up once the valve moved. At startup, a slow bulb response can be dangerous to the system due to permitting liquid to exit of the evaporator. This drawback was overcome by putting PVC tape between the bulb and evaporator wall. Then, a comparison of the response to traditional operation is examined.

Stoecker [51] studied evaporator and its model instabilities and tried to find a feedback loop through a system and build a replacement disturbance model approach. This is often accomplished by the output response insulating issue. If the new disturbance has amplification, a new round of model modification is needed. Additionally, if the amplification is larger than unity, the new disturbance is larger than the first disturbance and, in turn, the feedback can build operation unstable. The author focused on soundness of a valve-evaporator system and makes an analysis within the transport lag and the time constant in order to analyze the thermal capability and, hence, to adjust a stable loop.

2.2 Two-Zone Model

A two-zone model for evaporator has been developed based on basic laws of conservation of mass, momentum and energy equations. This model is capable of simulating evaporator transients by handling the two-phase flow as a dynamic element. If the two-phase length exceeds the length of the evaporator, the mean void fraction becomes a dynamic part. Thus, the evaporator exit quality is calculated. Misdistribution of flow among the evaporator passages is allowable by prescribing a top quality quantitative relation, wherever this quantitative relation permits the recess quality into every variable. The individual passage flow determined performance and evaluating the pressure drop across the evaporator passages.

De Bruijn *et al.* [52] created a two-zone model to achieve insight interactions between the valve and evaporator. In the model, the impact of the bulb thermal resistance was examined by adjusting the bulb contact space via evaporator. They end with that either increasing or decreasing the bulb resistance can cut back and, in turn, considered in the model. Increasing the temperature resistance gave high system damping. Therefore, decreasing the temperature resistance is recommended for such evaporator application. The model applied via static superheat from 4.4°C to -2.2°C, but do not report, however, a negative static superheat. Additionally, it was not obvious what level of superheat for the bulb. The model results are compared with experiments and sensible agreement was obtained. The model applied in oscillation rate between 10.5 and 12.4 g/sec, and also the exit temperature fluctuated between 3.2°C and 4.9°C. The magnitude of the superheat and corresponding oscillations were not reported.

Wedekind and Kobus [53] developed identical single tube two-zone model that predicts the transient response of the evaporator by employing a weighted average of the individual passages. They used the mean void fraction theory to model a multi-tube evaporator with thermal and flow misdistribution, whereas the flow spatiality came from different flow rates.

Grald [54] used a lumped parameter approach model of two-zone approach for simulating the evaporator. The model considered the lumped parameter approach, as it is the best fitted to simulating system interactions. Additionally, it avoids the process intensity of distributed modelling. He applied two normal differential equations to predict the ever-changing length of two-phase flow and relative density via evaporator. The model simulation used CFD technique. The iterations were done as a guess for the first input for the evaporator pressure. Then, the length of the two-phase region and relative density differential equations are converged and the temperatures and flow rates were calculated. The model was compared to experimental work using rate disturbances between 68 and 73 g/s. They found that the superheat could respond quicker to a step decrease than to a step increase.

Dhar and Soedel [55] created a two-zone model for traditional evaporator operation. They divided the traditional evaporator into two regions: one for the liquid and another for the vapor. They assumed that the liquid getting into the evaporator separates from the vapor, and then the liquid sits at all-time via the evaporator coil. As liquid boils, the vapor flows through the evaporator and becomes superheated. Empirical parameters were then combined with the conservation equations for the model. Simulations were conducted that the gain is simply too massive for valve unstable conditions, however if the gain is simply too small the system can take a protracted time to achieve its supposed operational conditions.

2.3 Distribution Model

Wang and Toubert [56] presented a distribution model using a computer code program. The model can optimize evaporator performance and with considerable accuracy. The model simulation is validated with three experiments and showed a steady state responses to completely different step functions. Jia *et al.*, [57] tried to enhance evaporator model under the condition of refrigerant pressure drop within the evaporator. The model was able to predict the distribution of refrigerant rate, void fraction, and temperature in time. Additionally, the model can deal with the transient response of the superheat flow to a step modification within the flow process. The model results showed that the superheat response is quicker, while the flow is decreasing. The superheat section of the tube affects the time required for the flow to reach steady-state following a rise in flow. This finding agrees with the two-zone model, as discussed early.

Gruhle and Isennann [58] developed a distributed model for evaporator. Different variable effects long evaporator are studied, as air temperature, condenser pressure, and compressor speeds. They additionally tried to elucidate random fluctuations within the dry-out location. They steered the random behavior of the two-phase flow length because of the non-linear behavior of the heat transfer constant within the region. The model also considered both steady state and oscillations conditions. Nyers and Stoyan [59] additionally developed a distributed model for evaporator as well as condenser and expansion valve. The evaporator in the model was assumed to be a bundle of parallel pipes, 10 m long, and enclosed by flowing water. They assumed the refrigerant was equally distributed among the tubes and also the flow conditions were a similar within all pipes. Seemingly, this model could be simplified into a one-tube model. The model could take into account of different parameters (water temperature, velocity, valve constant, compressor speed, and condenser pressure) to figure out a minimum stable working conditions. However, they failed to do so. Instead, they centered on modelling the system response to a tenth curved oscillation of the condenser temperature. A defect in modelling response and pressure distinction may be seen in the results of the model analysis and the model does not reply into many temperature changes or the accumulated convection constant, and also the curved oscillations persist.

Yasuda *et al.* [60] were curious about developing a mathematical model to predict evaporator transient conditions. The model enclosed, in addition to evaporator, the compressor, condenser, and expansion valve. The model forward a linear relationship between the mass flow and superheat and the maximum flow is resolved from manufacturer's knowledge. In the model, the two-phase refrigerant flow within the evaporator was simplified by employing a lumped issue, however a distributed model was employed in the superheat region. Characteristic values for the evaporator, like the mean void fraction, native void fraction, and evaporator pressure drop, were determined from experiments. The model simulation results were compared to experiments via three different simulations started at steady-state condition. The model was tested from 8.5°C to 10.5°C, wherever the refrigerant superheat responded with a straight line steady-state condition. In the model simulation 10.5°C to 6.5°C resulted in underdamped superheat oscillations, principally damped out. The third model simulation in static superheat was from 7.2°C to 3.0°C and the superheat temperature was shown to oscillate with no signs of damping.

2.4 Qualitative Model

Najork [61] investigated a dynamic behavior model of evaporator with the intention of finding causes of instabilities. He developed a loop diagram of temperature and pressure changes. The author realized that the evaporator stability is directly influenced by the working conditions. He also reported that a refrigeration loop are going to be stable if the essential gain is not exceeded by the temperature limits. He then suggests some methods for the stability working condition, as decrease the bulb modification in evaporator superheat by adding resistance between the bulb and evaporator to damp out speedy bulb temperature oscillations at the evaporator exit.

Schoen [62] found a fluctuation in the bulb temperature and within the evaporator pressure. The author explicit that the majority searching issues in the bulb temperature are unsteady. Different potential issues were listed which induce bulb temperature fluctuations, as follows. (1) Bulb location: if not properly placed on the evaporator, the bulb could live the oil temperature or pools of liquid that collect and obtain washed away. (2) Load misdistribution: the air-side flow misdistribution could offer the evaporator unbalanced heat transfer. Also evaporating rates among passages could result in the bulb sensing different superheats. (3) Refrigerant misdistribution: almost like load misdistribution, refrigerant misdistribution can also result

in completely different superheats being perceived by the bulb at the evaporator exit. (4) Low refrigerant speed: low speed could result in separated flow wherever, looking on the evaporator pure mathematics and the liquid refrigerant could pool up; if enough liquid becomes unfree within the evaporator a flow excursion is feasible, resulting in a sudden decrease in exit superheat. (5) Maintenance: if the system is not properly cleansed, foreign material could have an effect on the system behavior.

2.5 Chaos Model

The non-linear behavior of two-phase flow through an evaporator might have some fascinating consequences. The instabilities in evaporating flow are chaotic in nature. Lahey *et al.* [63] analyzed the evaporator stability drawback by developing a lumped parameter model to review density wave instabilities and searching for chaos within the system. Differential equations were used for the inlet speed, exit density, boiling boundary, and a length representing the mid-point physical property for the liquid single-phase region. The model assumed that sub-cooled liquid enters the evaporator as single-phase and exits the evaporator as a two-phase fluid. They found that the chaotic behavior was caused by the boiling boundary approaching the tip of the evaporator that caused the water speed to decrease.

2.6 Dynamic Modelling of Solar Evaporator

The mathematical model of solar evaporator was obtained from the appliance of the mass, energy, and momentum balance equations for the refrigerant fluid and energy balance for the tube wall. This provides the initial and boundary conditions used for the answer of differential equations, to perform a theoretical and experimental analysis of solar evaporator. Additionally, solar evaporator implies a complexness of the phenomena associated with the heat transfer method because of the variation of radiation, wind speed and therefore the condensation of vapor via regions on the external surface of the solar evaporator; that affects the transient behavior of the working conditions.

The model of the solar evaporator takes into account of many vital parameters to characterize the dynamic behaviors, which applied new developed correlations for the internal convective coefficient. The variations within the transient condition is accurately calculated and these values are often distant from the particular condition of the fluid within the evaporator at the first start up condition. The variations in parameters, like the initial condition of the refrigerant within the evaporator, the close temperature, the radiation and therefore the wind speed are vital in the modelling. In case of high degree of superheat, the model is tuned by a reduction within the boiling region and consequently increasing the dry space. Consequently, important to ceaselessly adjusts the fluid flow into the evaporator. The employment of this model can save time and computational resources. The model may be a great tool for the analysis of behavior in transient and steady state simulations conditions, together with variations in radiation, temperature, wind speed and part conditions.

2.7 Air Cooled Tube-fin Model

The air cooled tube-fin model is a numerical-analytical approach to study evaporator mounted in automotive at high variations of air temperature and humidness conditions. The mathematical model is predicated under the following assumptions: (1) Within the evaporating region, the liquid and therefore the gas phases of the refrigerant area unit incompressible and in equilibrium. (2) The two-phase evaporating flow within the coil is taken into account as a homogenous, one-dimensional flow within the z -direction. (3) Variations of refrigerant kinetic and mechanical energy area unit unheeded. (4) Axial heat conductivity inside every pipe is neglected. (5) The flow assumed to be adiabatic. The mathematical model takes under consideration the refrigerant pressure drops within the tube. The properties of the steady state, which represents the initial state of the phase space, are analyzed by coupling numerical and analytical strategies. The numerical resolution in the model has shown that the behavior of the model is congruent with this plant values. Moreover, the numerical results have allowed to find the interface and validity of the linearized model for the vapor region. Within the analytical framework, the two-phase and therefore the single-phase regions are examined. The chemical analysis of the nonlinear two-phase flow has achieved the estimates on the information. As for the vapor region, the model has supplies the express law of variation of the refrigerant temperature on every pipe of the superheated circuit. In the model, the express dependence on the mass flow-rate and therefore the different model parameters has been obtained. Ensuing developments of this analysis can concern the study of the transient response of variations on freelance management parameters.

2.8 Dynamic Mathematical Model

The development of a dynamic mathematical model (DMM) of a three-evaporator air-conditioning system is suggested by researchers. The DMM model was designed based on sub-models of major system elements. Not like other models, the DMM model developed specifically under consideration of smart and heat transfer balances. The model used MATLAB programming interface where evaporator in the model was divided into two regions, i.e., a two-phase and a superheated region. The two-phase region was divided into a liquid (L) and a vapor zone (V). The model was validated with experimental data. Model predictions were found to be in range of $\pm 6\%$ of the measured values. The model was capable of simulating each steady state and dynamic operation of evaporator system with a suitable modelling accuracy. Therefore, the model is thought to be helpful in defining operating performances and developing novel controllers of system working conditions. In the model, evaporators with different cooling capacities and operative conditions could share a typical refrigerant pressure at compressor suction pipe and a typical compression pressure. The operative parameters in evaporator will definitely interfere with other system components, causing a tough modelling. It is thus expected that the model is used as an efficient platform in finding out the operative performance, and developing advanced management ways of system.

2.9 Advantages and Limitations of Different Evaporator Models

Evaporator-modelling tools are needed to be improved in many ways based on the shortcomings of the current models in literature, as discussed next. First, there are few multi-passage models for understanding evaporators' dynamic multi-passage issues. Evaporator models are required to accurately predict system behavior. In these multi-passage evaporator models, flow misdistribution additionally must be taken into consideration. This leads failing to ought addresses single-passage evaporators, however multi-passage evaporators expertise quality misdistribution and completely different levels of superheat at the evaporator exit. Many evaporator models additionally ought to develop and simulate liquid exit from the evaporator. Having liquid enter the suction line will harm the compressor, nevertheless few models will support the transition from associate exit superheat to associate exit quality. Investigations into searching additionally ought to refine. Several simulations making use of a regulator enlargement about the vital system parameters. For instance, few enlargement models have enclosed the consequences of bulb and evaporator pressure on the diaphragm. Instead, some trust solely on associate passageway equation to predict the flow rates into the evaporator solely taking the consideration of the pressure drop across the passageway and neglecting, however, pure mathematics affects the system dynamics. Lastly, suggestions are needed to reduce the system response to bound conditions, however while not understanding the physics and dynamics of the system it's troublesome to work out developments.

3. CONCLUSION

Over the past few decades, evaporator studies had become more and more widespread. The studies focused on improvements and developing of evaporators of automobiles. Understanding evaporator dynamics and the way it works is essential for quality modelling process. There are some factors influencing performance of the evaporator, as if the two-phase region gets close to the exit of the evaporator and the system does not have an accumulator, liquid droplets might enter the suction line and harm the compressor. This paper presents a review study of evaporator and its modelling. Eight different models are presented and discussed in the study. Strong and weakness in each model are also covered in the study. Such review study is thought not introduced previously, according to the best of author knowledge.

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