Development of Efficient Air Conditioning and Refrigeration System for Service Vehicles

Mohammed Saif Siddiqui[1], Atul Kumar Tiwari[2]

M.Tech. (ME) Scholar, Sagar Institute of Technology and Management Barabanki U.P. India 225001

Abstract: ***This thesis aims to develop a proof-of-concept demonstration of a high efficiency vehicle air conditioning and refrigeration (VACR) system to be employed in service vehicles. The work herein is part of a collaborative research project with two local companies: Cool-It Group, and Saputo Inc., with a main focus on service vehicles. Due to global energy consumption and the environmental impacts of air conditioning and refrigeration (A/C-R) systems, the development of a high efficiency system can significantly contribute to green and sustainable development and environmental Protection. This thesis fills a gap in the literature by developing real-time thermal and performance characteristics of the VACR systems employed in the food transportation industry. Field data is acquired from pilot refrigerated service vehicles during different seasons of the year and the duty cycles are established. The acquisition of field data begins in stationary A/C-R systems and continues in mobile VACR systems. Moreover, a test bed is built in the Laboratory for Alternative Energy Conversion (LAEC) for more comprehensive experiments. Mathematical models are developed for thermal and performance simulations of VACR systems under steady state and transient operating conditions. The models are validated using the laboratory and field data and employed for a thermal and performance investigation of VACR systems. A proof-of-concept demonstration of high efficiency VACR systems is built in LAEC using variable speed compressor and fans and high efficiency heat exchangers. The modeling results are validated and used to develop an optimization model. The optimization model is validated and utilized to determine the optimum compressor and fans speeds for achievement of the highest coefficient of performance (COP) under real- time operating conditions. The optimization model is integrated with an existing cooling demand simulator to develop a proof- of-concept demonstration of a proactive and model predictive controller (MPC) for the VACR system. The controller is implemented on the laboratory-built VACR system and a proof-of- concept demonstration of high efficiency VACR is finalized. The developed concept and platform is expandable to the entire transportation industry as well as stationary A/C-R systems.***

Keywords: Vehicle Air conditioning and Refrigeration, Performance Optimization and Mathematical Modeling

1. Introduction

1.1 Thesis Background

Despite widespread attention during the past decades, there is a significant potential to reduce energy consumption and greenhouse gas (GHG) emissions from energy systems all around the globe. Based on the fifth report from Intergovernmental Panel on Climate Change released in 2013, the average global surface temperature has increased by 0.85 K during 1880-2012, which accelerates the rate of glacier melt and sea level rise [1,2]. Among all the energy sectors in the world, the transport sector is responsible for 22% of global CO_2 emissions, which significantly contribute to global warming [3,4]. Around 31% of the food supply chain includes refrigerated transportation [5,6]. Furthermore, about 20% of total global refrigerant emissions come from mobile air conditioning and refrigeration systems [7].

Air conditioning and refrigeration (A/C-R) systems are used in many stationary and mobile applications to provide either comfort conditions for people or an appropriate condition for food and other temperature/humidity sensitive creatures/products. These systems consume a tremendous amount of energy leading to large quantities of GHG emissions. In the U.S., A/C-R systems consume more than 20% of the total energy used in residential buildings and more than 25% in commercial buildings [8]. It was reported that more than 26 billion liters of fuel oil is consumed each year just to run air conditioning systems in light-duty vehicles in the U.S. [9,10]. Running vehicle air conditioning and refrigeration (VACR) systems increases higher fuel consumption in compact-midsize vehicles by 12-17% [11,12].

Most existing A/C-R equipment operates based on the vapour compression refrigeration (VCR) cycle and consists o a compressor, a condenser, an evaporator, an expansion valve, and fans. A schematic of the basis VCR cycle is shown in Figure 1-1. In this type of refrigeration cycle, the compressor, the most energy-consuming component, sucks the refrigerant gas from the evaporator and, after compressing it, pumps the high- pressure, high temperature gas into the consider. Through the condenser, the gas is condensed and the latent and sensible heat is rejected to a secondary flow (usually air, in VACR application). The saturated or sub-cooled liquid from the condenser then goes to the expansion valve. As a result of throttling through the expansion valve, the pressure and temperature of refrigerant drops drastically and a low pressure, low temperature two phase refrigerant flows into the evaporator where the refrigerant evaporates. The evaporation absorbs heat from a secondary flow and cools it down. The evaporated refrigerant, in the form of saturated or super heated gas, is then sucked in again by the compressor and one cycle is completed (13, 14)

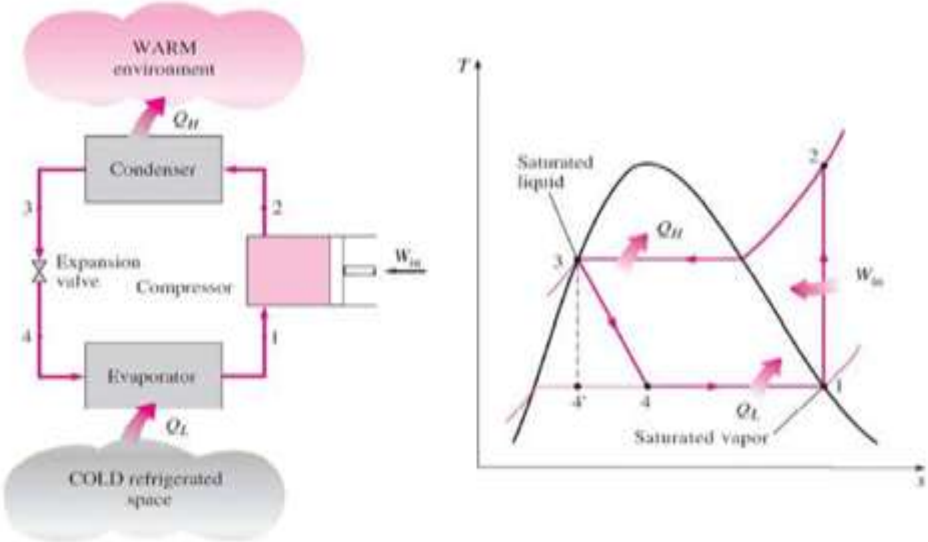

Figure 1-1: Schematic of a basic VCR cycle [14]

The efficiency of A/C-R systems is defined by the coefficient of performance (COP), which is the ratio of the cooling power output to the input power consumption. A/C-R systems in transportation applications operate in a harsh environment (intensively variant) and experience a wide range of cooling demand and constraints imposed by available space and weight. As such, these systems have lower COP (usually less than 1.5) than stationary systems (usually larger than 3) [15–18]. In addition to the low COP, the quantity of transported goods, amount of home delivery, and expectations for the quality of goods are increasing, resulting in a tremendous amount of energy consumption by the refrigerated transport industry [19,20]. Furthermore, the globalized nature of food production has led to longer transit distances for many food products [21]. In the U.S. alone, it is estimated that processed foods are, on average, transported over 2,100 km before being consumed and fresh food products 2,400 km [21,22]. In addition, delivery of food products requires frequent opening of the door, which leads to air infiltration and a remarkable increase in the cooling demand. It is reported that a food product can be subjected to as many as 50 door-openings during a delivery [23]. The low performance, combined with the harsh operating conditions, lead to significant global impacts and put high pressure on the food industry to find remedies to reduce the energy consumption of refrigerated transport [19].

1.2 Thesis Motivation

Due to the low COP of the numerous VACR systems worldwide, any small improvement can bring a significant global impact. The relatively low COP of VACR systems is in part due to more frequent and inefficient on-off cycling of these systems, which is a result of the lack of intelligent control modules, the small size of the systems, and a more intense load variation. The more intense load variations in VACR systems are due to poor compartment insulation, the high frequency of opening and closing doors or windows, sun exposure, and movement of the vehicle.

Accordingly, development of an optimally controlled, proactive VACR system with higher efficiency to replace existing inefficiently controlled VACR systems will have significant global improvement on energy consumption and the corresponding GHG emissions. The optimally controlled VACR system is equipped with a variable speed compressor and variable speed fans that enable the capacity of the system to be controlled instead of using on-off cycling. The focus of this research is on service vehicles; however, the developed concept and system could be used in all sectors of the transportation industry.

The work herein has been prompted by a collaborative research project with two local companies; Cool-It Group, an Abbotsford, BC based manufacturer of anti-idling battery-powered VACR systems for truck and vans; and Saputo Inc., Canada's largest dairy product processor, located in Burnaby, BC. The low COP of battery-powered VACR systems leads to a relatively short life for the batteries and highly affects the reliability of Cool-It's products. Also, Saputo spends an enormous amount on fuel for their refrigerated trailers that are used to deliver dairy products every day. Due to the impact of VACR systems on countrywide fuel consumption and the environment, this research project is financially supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) through an Automotive Partnership Canada (APC) Grant, No: APCPJ 401826-10.

1.3 Thesis Scope

Based on the reported low performance and significant global impacts of VACR systems and as a result of collaboration with two local companies; Cool-It Group and Saputo Inc., this research is focused on developing high efficiency VACR system for service vehicles. The objectives of the research are to: 1) establish the duty cycle and actual operating conditions for refrigerated (delivery) service vehicles, 2) investigate the performance of VACR systems under real-time operating conditions employing mathematical techniques and experimentation, 3) demonstrate a proof-of-concept for optimization-based, model predictive control of VACR systems, and 4) provide a platform for proactive prediction and control of VACR systems over the duty cycle. As such, an experimental setup is developed to perform in-lab data acquisition and obtain the real-time performance characteristics of VACR systems. In addition, comprehensive field data is collected to establish the duty cycle(s) and obtain real-time thermal behavior and performance characteristics of the VACR systems. Mathematical models are developed and validated to simulate thermal and performance behavior of VACR systems under steady state and transient conditions. Furthermore, a proof-of-concept demonstration of a high efficiency VACR system based on variable speed compressor and fans and high efficiency heat exchangers is developed.

A model-based optimization method is employed to determine the optimum compressor and fans speeds under any imposed operating condition. Finally, an in-lab proof-of-concept demonstration for proactive and optimal control of VACR systems by integrating the developed model- based optimizer with an existing cooling demand simulator is developed. The developed concept and platform can be expanded to the entire transportation industry and even stationary systems and will lead to significant global energy savings and GHG reduction.

2. Literature Review

A/C-R systems have been the topic of many studies in the last decades due to their significant global energy consumption and corresponding environmental impact. In spite of numerous studies in the literature focusing on the stationary A/C-R systems in different applications, the number of studies relevant to general category of VACR systems is limited [24–30]. In addition, most VACR-related studies have concentrated on engine-driven car A/C-R systems rather than the service vehicle category. Furthermore, the literature lacks an in-depth study on performance optimization of VACR systems in service vehicles. The literature review is represented in two separate categories: 1) thermal and performance studies on A/C-R systems, 2) control studies on A/C-R systems.

2.1 Thermal and performance studies on A/C-R systems

The majority of the studies in the field of VACR systems are related to the assessment of the effects of refrigerant type on the characteristics and the performance [30–34]. Yoo et al. [33] studied the performance of an automotive air conditioning system charged with R152a, and compared it to R134a. The results of this study showed that the R152a system was slightly better than R134a not only under driving conditions, but also under idling conditions. Brown et al. [34] compared a VACR system charged with CO_2 and R134a, and showed that the R134a refrigerant led to a 21-34% higher coefficient of performance (COP). Cho et al. [30] experimentally compared the characteristics of a VACR system charged alternatively with R134a and R1234yf, and showed that using R1234yf resulted in a relatively lower compressor power consumption and cooling capacity by 4% and 7%. They also investigated the effectiveness of installing an internal heat exchanger for heat transfer between cold refrigerant leaving the evaporator and warm refrigerant leaving the condenser to increase the amount of sub-cooling and found a 4.6% improvement in COP. A variety of other important parameters including refrigerant charge, compressor speed, fan speed, and ambient temperature have also been considered in VACR system studies. Ratts et al.

3. Mathematical Model Development

Mathematical simulation of A/C-R systems is an effective method for investigating the thermal behavior and thermodynamic characteristics of these systems and to obtain the power consumption, cooling power, and COP under any operating conditions. A mathematical model for a complete A/C-R system is an integration of the component sub-models, including the compressor, condenser, evaporator, and expansion valve. Therefore, a detailed analysis of each component in an A/C-R system is covered during the modeling procedure. The detailed component analysis in the mathematical modeling results in a complex set of conservation equations that should be solved numerically [25,26]. Thus, a numerical algorithm and a solver should be developed to simulate VCR systems.

In Figure 2-1, a schematic of a basic A/C-R system and the main thermal/thermodynamic parameters used in the mathematical modeling are presented. In this chapter, the mathematical modeling of such a system is presented in three sections: 1) steady state model, 2) quasi-steady state model, 3) transient model.

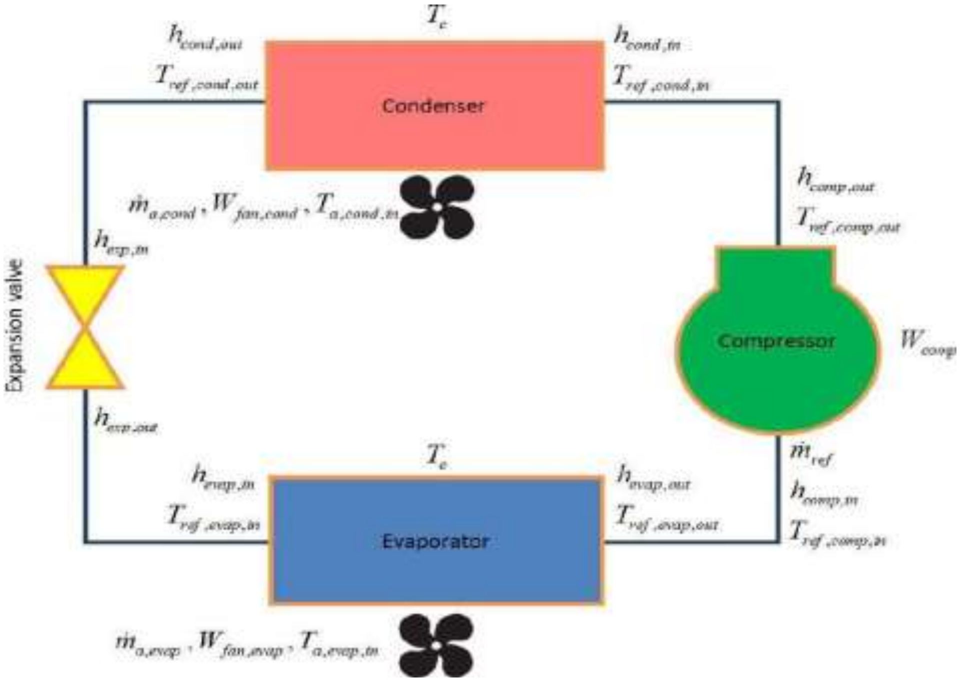

Figure 2.1: Schematic of a basic A/C-R unit and the main parameters

3.1 Steady State Model Development

In this section a steady-state mathematical model for investigating the thermal/thermodynamic behavior of A/C-R systems under various steady state operating conditions is developed. The steady state model is a basis for the development of the quasi-steady state and fully transient models and is employed to perform a comprehensive parametric study of the characteristics of the system. The major output parameter from the modeling of an A/C-R system is the COP. In addition to the COP, other salient parameters of an A/C-R system that are obtained from the modeling include the cooling power, input power (sum of compressor, evaporator and condenser fan powers), and refrigerant mass flow rate. An integration of the component sub-models of an A/C-R system forms its complete mathematical model [70].

3.2 Compressor sub-Model

A map-based model is used in this study for thermodynamic simulation of the compressor under steady state conditions. It has been experimentally shown that this approach had a good agreement with experimental data [49,71,72]. Second-order polynomials are developed for the compressor input power and refrigerant mass flow rate quantities based on the manufacturer's test data, as shown in Eqs. (2.1) and (2.2) in Table 2-1. These equations yield a maximum of 2.5% discrepancy when compared to the manufacturer's data. It should be noted that the manufacturer's data is usually provided for fixed magnitudes of superheating and sub cooling. If the A/C-R system is equipped with a thermostatic expansion valve, the refrigerant flow rate is controlled to achieve a pre-set amount of superheating. Accordingly, throughout the duty cycle the degree of superheating at the outlet of the evaporator is kept nearly constant. However, the degree of sub cooling varies, depending upon the imposed conditions on the system from the air- stream sides at the condenser (major impact) and evaporator (minor impact). Therefore, a modification will be required for different degrees of superheating and sub cooling. In the present research, wide ranges of superheating and sub cooling (0-15^{0}C) are tested and the modified correlations of the compressor model under different superheating and sub cooling values are obtained. The refrigerant side thermodynamic correlation for the compressor is presented in Eq. (2.3), as seen in Table 2-1. Based on these correlations, with known inlet conditions at the compressor inlet, the state point of the refrigerant gas at the compressor discharge can be calculated.

3.3 Condenser and evaporator sub-model

Energy balance correlations between the refrigerant and air flow in condensers and evaporators are used to model heat transfer in these components of the A/C-R system. In the present study, we follow Shah and Sekulic [73], and an ε-NTU model is used to derive the mathematical model for the condenser and evaporator. In this approach, the effectiveness ε is defined as the ratio of the actual heat transfer to the maximum possible heat transfer; see Eq. (2.4) of Table 2-1. The maximum possible heat transfer happens when the temperature of one stream at the outlet reaches the inlet temperature of the other stream and is defined in Eq. (2.5). The actual heat transfer between the air stream and refrigerant flow can be calculated using Eq. (2.6). To use this equation, it is required that ε be found from Eqs. (2.7) and (2.8). For the current study, the condenser and evaporator specifications are obtained from the manufacturer's datasheet and drawings. In addition to the ε-NTU correlations, which represent the heat transfer between the air and refrigerant streams, correlations of enthalpy change for both the refrigerant and air streams should be added to complete the heat transfer model for the evaporator and condenser. Equations (2.9) and (2.10) represent the enthalpy change for the air and refrigerant streams in the condenser and evaporator. The cooling capacity of an A/C-R system is obtained using either of these equations (Eq. (2.9) or (2.10)) when written for the evaporator. Also, the total heat rejection of the system is calculated using either of these equations for the condenser. For the air stream in the evaporator, the enthalpy is calculated based on the temperature and relative humidity to include both the sensible and latent heat transfers. However, for the air stream in the condenser, the enthalpy of air can be simply found using the temperature and thermal capacity of air since there is no water condensation on the condenser coil.

It should be mentioned that two heat transfer regimes exist in the evaporator: 1) two- phase heat transfer, relevant to the saturated zone; and 2) single-phase heat transfer, relevant to the superheated zone. Also, the condenser can be divided into three heat transfer regimes: single-phase superheated; two-phase saturated; and single- phase subcooled. Due to governance of different convective heat transfer equations for the mentioned regimes, in this study the evaporator and condenser are divided into two and three sub-zones, respectively. Thus, the ε- *NTU* model is applied for each sub- zone separately to achieve a high level of accuracy. In addition to the heat transfer model for the condenser and evaporator, map-based correlations are employed to obtain the power consumption of the fans using manufacturer's datasheets [74], see Eq. (2.11) in Table 2-1.

Table 2-1: Mathematical model correlations

Compressor sub-model	$W_{comp} = c_0 + c_1 T_e + c_2 T_c + c_3 T_e^2 + c_4 T_e T_c + c_5 T_c^2 + c_6 T_e^2 T_c + c_7 T_e T_c^2 + c_8 T_e^2 T_c^2$	(2.1)
	$\dot{m}_{ref} = d_0 + d_1 T_e + d_2 T_c + d_3 T_e^2 + d_4 T_e T_c + d_5 T_c^2 + d_6 T_e^2 T_c + d_7 T_e T_c^2 + d_8 T_e^2 T_c^2$	(2.2)
	$\dot{m}_{ref}(h_{ref,comp,out} - h_{ref,comp,in}) = W_{comp} \times \eta_E \times \eta_M$	(2.3)
Condenser and evaporator sub-model	$\varepsilon = \dot{Q} / \dot{Q}_{max}$	(2.4)
	$\dot{Q}_{max} = C_{min}(T_{hot,in} - T_{cold,in})$	(2.5)
	$\dot{Q} = \varepsilon C_{min}(T_{hot,in} - T_{cold,in})$	(2.6)
	$\varepsilon = \dfrac{1-\exp[-NTU(1-C^*)]}{1-C^*\exp[-NTU(1-C^*)]}$	(2.7)
	$C^* = C_{min}/C_{max}$, $NTU = UA/C_{min}$	(2.8)
	$\dot{Q} = \lvert \dot{m}_a (h_{a,in} - h_{a,out}) \rvert$	(2.9)
	$\dot{Q} = \lvert \dot{m}_{ref} (h_{ref,out} - h_{ref,in}) \rvert$	(2.10)
	$W_f = W_{f,nom}\left(cf_0 + cf_1\left(\dfrac{\dot{m}_a}{\dot{m}_{a,nom}}\right) + cf_2\left(\dfrac{\dot{m}_a}{\dot{m}_{a,nom}}\right)^2 + cf_3\left(\dfrac{\dot{m}_a}{\dot{m}_{a,nom}}\right)^3\right)$	(2.11)
Expansion valve sub-model	$h_{ref,TEV,in} = h_{ref,TEV,out}$	(2.12)
Refrigerant thermodynamic correlations	$h_i = f_1(P_i, T_i), T_e = f_2(P_e), T_c = f_2(P_c), cp_a = f_3(T_a)$	(2.13)

3.4Thermostatic expansion valve sub-model

Following Ref. [49], an isenthalpic model is selected for thermodynamic simulation of the thermostatic expansion valve. In this model, as a result of the adiabatic assumption, the inlet and outlet refrigerant enthalpies are considered to be the same, see Eq. (2.12) in Table 2-1.

3.5 Thermodynamic correlations for the refrigerant

In addition to the main component sub-models, a few thermodynamic correlations are also employed to add the refrigerant thermodynamic properties to the model. HFC-134a refrigerant is used in most VACR systems, including the main system studied in this research. Thus, the correlations between the thermodynamic properties of HFC-134a are obtained and employed [75]; see Eq. (2.13) Table 2-1.

3.6 Numerical solver

Developing the mathematical model for an A/C-R system, including the correlations shown in Table 2-1 and the condenser and evaporator overall heat transfer relationships, leads to a set of 20 coupled nonlinear equations that have to be solved simultaneously. The A/C-R system unknown parameters (x_1 - x_{20}), which are calculated using the mathematical model, are listed in Table 2-2.

$$\begin{cases} g_1(x_1 = Cooling\ power, x_2 = W_{comp}, \ldots, x_{20} = h_{ref,TEV,in}) = 0 \\ g_2(x_1 = Cooling\ power, x_2 = W_{comp}, \ldots, x_{20} = h_{ref,TEV,in}) = 0 \\ . \\ . \\ g_{20}(x_1 = Cooling\ power, x_2 = W_{comp}, \ldots, x_{20} = h_{ref,TEV,in}) = 0 \end{cases} \quad (2.14)$$

$$\begin{bmatrix} x_1^{n+1} \\ \cdot \\ \cdot \\ \cdot \\ x_{20}^{n+1} \end{bmatrix} = \begin{bmatrix} x_1^{n} \\ \cdot \\ \cdot \\ \cdot \\ x_{20}^{n} \end{bmatrix} - \begin{bmatrix} \frac{\partial g_1}{\partial x_1} \cdots \frac{\partial g_1}{\partial x_{20}} \\ \cdot \\ \cdot \\ \cdot \\ \frac{\partial g_{20}}{\partial x_1} \cdots \frac{\partial g_{20}}{\partial x_{20}} \end{bmatrix}_{x_i^n}^{-1} \times \begin{bmatrix} g_1(x_i^n) \\ \cdot \\ \cdot \\ \cdot \\ g_{20}(x_i^n) \end{bmatrix} \quad (2.15)$$

Table 2-2: Output parameters of the mathematical model

$\dot{Q}_{evap}$ (cooling power)	$\dot{W}_{comp}$ (compressor power)	$\dot{W}_{f,cond}$ (condenser fan power)	$\dot{W}_{f,evap}$ (evaporator fan power)	$\dot{Q}_{cond}$ (heat rejection)
COP (coefficient of performance)	NTU_{evap} (number of transfer units, evap.)	NTU_{cond} (number of transfer units, cond.)	ε_{evap} (effectiveness, evap.)	ε_{cond} (effectiveness, cond.)
T_c (condensing temperature)	$h_{ref,evap,in}$ (refrigerant enthalpy @ evap. inlet)	$\dot{m}_{ref}$ (refrigerant mass flow rate)	$T_{a,evap,out}$ (air temperature @ evap. outlet)	h_g @ T_e (saturated gas enthalpy @ evaporating temperature)
$h_{ref,comp,in}$ (refrigerant enthalpy @ comp. inlet)	$h_{ref,cond,in}$ (refrigerant enthalpy @ cond. inlet)	h_g @ T_c (saturated gas enthalpy @ condensing temperature)	h_f @ T_c (saturated liquid enthalpy @ condensing temperature)	$h_{ref,TEV,in}$ (refrigerant enthalpy @ expansion valve inlet)

3.7 Transient Model Development

As the final step of model development for the A/C-R systems, a fully transient model is developed in this section. This model includes all the transient terms of the energy equation. The aim of developing a fully transient model is to increase the accuracy of the mathematical model predictions beyond the modified quasi-steady model and employ it for investigations of the transient thermal and performance characteristics.

3.8 Condenser sub-model

Conservation of mass, momentum, and energy form a complete mathematical model for the condenser of an A/C-R system. In general, three different refrigerant regimes including: superheated, 2- phase, and sub-cooled may exist in a condenser thus, the governing equations are written separately for each of these regimes. Following [79,80] a schematic representative of the heat transfer regimes in a condenser is drawn in Figure 2-3.

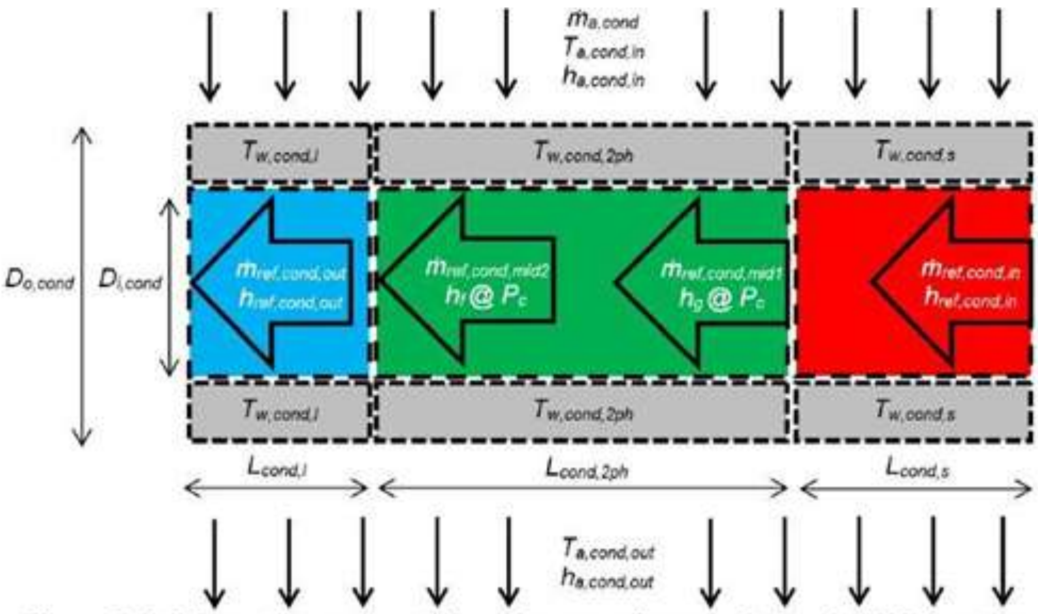

Figure 2-3: Schematic representative of a cross flow condenser in VCR systems (sections from right to left: superheated, 2-phase, sub-cooled)

4. Result and Future Work

4.1 Result of Thesis

In this thesis, a lab-scale proof-of-concept demonstration of high efficiency vehicle air conditioning and refrigeration (VACR) system is developed. The developed high efficiency system is scalable and can be expanded to all transportation and stationary applications. Due to tremendous global energy consumption and environmental impacts of air conditioning and refrigeration (A/C-R) systems, any improvement of these systems' performance significantly contributes to green and sustainable development and environmental protection. The work is initiated as collaboration with two local companies: Cool-It Group, and Saputo Inc., with main focus on service vehicles; however, the developed concept and platform is expandable to any size and application.

An in-lab testbed is built in Laboratory for Alternative Energy Conversion (LAEC) for performance investigation of VACR systems under different operating conditions. The test bed is first built using the components of a VACR system received from one of the industrial partners. A number of measuring equipment, an environmental chamber, and power supplies are utilized in the testbed. A Lab VIEW interface is developed for data collection that is featured with compressor and fans speed control later. The performance of VACR system is comprehensively investigated using the test results. The test bed is later upgraded using high efficiency heat exchangers and variable speed compressor and fans.

In addition to the in-lab experimental study, real-time field data is acquired from a stationary A/C-R system used in commercial refrigeration and VACR systems used in trailers of food transportation. The real-time thermal and performance characteristics of these systems are investigated under different duty cycles. The potential energy saving and GHG reduction is estimated.

Mathematical models are developed for thermal and performance simulation of VACR systems under steady state and transient operating conditions. The models are validated using the experimental and field data and used for performance investigations. The validated results are utilized for development of performance optimization model.

4.2 Future Works

The following research directions can be considered as the continuation of this study:

1) Implement the developed proactive, optimal, and model predictive concept on engine- driven VACR systems of trailers and other service vehicles and investigate the real-time performance improvement in such applications. Reduce the computational costs of model predictive controller by simplifying the models (e.g. find the dominant terms of optimization model and drop the insignificant terms).
2) Study the effects of using different types of refrigerant on the thermal and performance characteristics of the VACR systems.
3) Develop similar concept and platform for cascade refrigeration used in commercial systems.
4) Extend the developed concept to air conditioning and refrigeration systems in buildings and integrate it with building energy management systems to achieve the highest overall energy efficiency.
5) Equip the developed controller with additional features to enhance its comprehensiveness; for instance, defrost module can be added to the controller to avoid evaporator coil freeze in low temperature applications.
6) Develop a similar concept and platform for thermally-driven air conditioning and refrigeration systems or even heating systems in buildings and industries.

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