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Vapor compression refrigeration cycle for electronics cooling – Part I: Dynamic modeling and experimental validation

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ABSTRACT

This paper presents a first-principle lumped-parameter dynamic model and experimental validation of vapor compression cycles for electronics cooling. The model couples the dynamics of the heat exchangers with static empirical models for compressor and expansion valve. In contrast to past work on systems level modeling of refrigeration cycles, this paper focuses on imposed heat flux boundary condition, and the associated critical heat flux and critical vapor quality, in the evaporator. Using our vapor compression cycle testbed, we verify that the model prediction of the evaporator exit temperature and critical heat flux matches well with experimental measurements. The model is also used to search for operating conditions to enhance the critical heat flux. Experimental results show that at an undesired operating condition, even a small 5% change of heat flux could cause a wall temperature spike of over 100 °C, in contrast to 15 °C at a more advantageous operating conditions. For large heat flux transients, the onset of critical heat flux condition may be delayed, but its avoidance may require active refrigerant flow control.

1. Introduction

With the proliferation of high power photonic devices such as light emitting diodes and laser diodes and increasing density of electronics, there is a significant need for thermal management solutions to achieve efficient heat removal at the device level and energy efficiency at systems level [1]. This need is especially evident in new military vehicles, such as all-electric ships, hybrid ground vehicles, and high maneuverability aircrafts. In the conceptual design of electric ships, up to 28 MW of waste heat has to be dissipated from various sources, including high-power radars, electric weapons, and advanced fuel cells. Advanced thermal management is critical for achieving high power densities and reliability in such systems [2,3]. Vapor compression cycle (VCC) has emerged as a promising candidate technology [4,5], combining high heat transfer coefficients at device level and potentially high cycle efficiency. Furthermore, VCCs can be used to cool multiple heat sources using the same main refrigeration loop, increasing the overall efficiency of the system [6].

VCC for high power electronics cooling differs from traditional refrigeration cycles in two significant aspects: (1) There is an imposed heat flux as the boundary condition at the evaporator in contrast to an imposed inlet temperature difference. (2) There are large and rapid transients in heat loads versus mostly constant heat load [7]. In traditional VCC, the boundary condition at the evaporator is a temperature difference; changes in heat load are slower due to the convection process inherent in the fluid to fluid heat exchangers. Large transients are only expected during system start-up or shut-down operations [8]. In electronics cooling, dry out condition may be encountered during transient heat load. When the critical heat flux (CHF) is reached, temperature could rise sharply leading to burnout of the electronic device.

Critical heat flux is defined as the heat flux that for specific operating conditions (geometry, mass flow rate, and pressure) will cause heat transport deficiency at the boundary of the heated wall, resulting in sudden and rapid increase in the surface temperature [9,10]. In systems with a prescribed temperature difference boundary condition, such as refrigerators or air conditioning systems, the drop in heat transfer coefficient produces a drop in the total heat being transferred at the evaporator. It would reduce the cycle efficiency, without inflicting damage to the system. In traditional VCC, the exit of the evaporator is always superheated vapor (Fig. 1(b)). For VCC in electronics cooling, the exit of the evaporator should be maintained in the two-phase (liquid–vapor) flow region to avoid CHF. Hence the addition of an accumulator (Fig. 1(c)) or other

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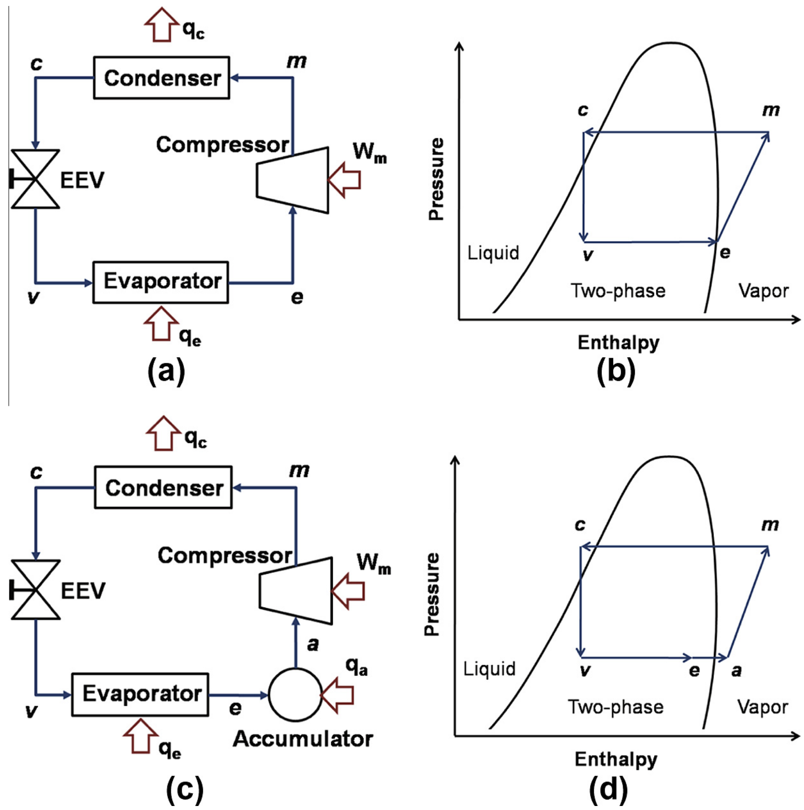

Fig. 1. Vapor compression cycle (a) Schematic of system components for traditional VCC (b) thermodynamic cycle of a traditional VCC in a Pressure vs. Enthalpy diagram where the exit of the evaporator and inlet to the compressor is saturated vapor (c) Schematic of system components for VCC for electronics cooling (d) thermodynamic cycle of VCC for electronics cooling in a Pressure vs. Enthalpy diagram where the exit of the evaporator is a liquid–vapor mixture.

type of system modification is required to guarantee safe operation of the compressor (Fig. 1(d)).

This paper develops a comprehensive VCC dynamic model for systems with imposed heat flux at the evaporators (as in the cooling of high-power electronics). The heat exchangers, i.e., evaporators and condensers, are approximated by their spatially averaged behavior (one-zone model, since the distributed behavior is approximated by a single set of lumped variables). The dynamic model includes prediction of the CHF condition by modeling the vapor quality at the onset of CHF (x_{crit}). Experimental validation is performed away and around the CHF condition. The refrigerant used in the experimental system is R134a and the thermodynamic properties are obtained from published data by the National Institute of Standards and Technology (NIST) [11]. The model is also used to improve the operating condition by increasing CHF or reducing power consumption. The improved operating condition is shown to withstand a step heat load change versus a nominal operating condition which exhibits rapid temperature rise.

2. VCC modeling

Dynamic models for VCCs include four main components: evaporator, compressor, condenser and expansion valve [12]. The evaporator and condenser are modeled using mass, momentum and energy conservation equations. Expansion valve and compressor are modeled using static equations involving empirical parameters (discharge coefficient, and volumetric and isentropic efficiencies). The evaporator and condenser are distributed parameter systems modeled by a set of partial differential equations [13,14]. There are a number of lumped-parameter approximation approaches driven by systems level design and control needs [15–17]. The lumped-parameter model is suitable for analysis and design iteration as it is much less computationally demanding, but also at much lower accuracy especially during start-up transients [18].

In traditional VCC systems, the evaporator is usually divided into two regions: a two-phase region from the entrance of the evaporator until the flow reaches a saturated vapor condition, and a second region for superheated vapor. Similarly the condenser is divided into three regions: a superheated vapor region, two-phase region and a subcooled region. The length of these regions varies with time and are modeled as additional state variables. This formulation is referred as the moving-boundary method [19,15]. One challenge of this approach is that during large transients some of these zones disappear or are created which result in varying number of dynamic states. In [20], a multi-model approach is proposed with switching between them as needed. In [21], a pseudo-quality is used that can be larger than one in the evaporator or lower than zero in the condenser, avoiding the need for model switching. This formulation is simpler to implement and is expected to perform well for evaporators operating close to the saturation condition, hence it is selected in our research.

We impose the following assumptions to simplify the physical model:

- Two-phase flows in evaporator and condenser are considered homogeneous and in thermal equilibrium.
- Axial heat conduction in evaporator and condenser is negligible.
- Pressure drop in evaporator and condenser is neglected.
- Dynamics of compressor and expansion valve are much faster than that of the heat exchangers and are modeled as static components.
- The complete system is perfectly insulated (no heat losses or heat gains from the ambient).