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# Hardware-in-the-Loop Load Emulation for Air-Conditioning and Refrigeration Systems

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## ABSTRACT

This paper presents a novel approach for experimentally simulating various environmental conditions and container parameters on air conditioning and refrigeration (AC&R) systems. The proposed emulation technique uses a hardware-in-the-loop (HIL) system to simulate the loading conditions on the evaporator during experimental testing. The evaporator air inlet conditions are controlled with a small emulation unit attached to the evaporator, analogous to a dynamometer attached to an engine for laboratory testing. An on-line real time model, with the parameters of the container being simulated, is used to determine the virtual container temperature. The emulation unit then tracks this virtual container temperature by mixing the proper amount of evaporator output air with ambient air. The on-line model takes in measurements from the experimental system to determine the cooling rate of the virtual container. Load emulation ultimately allows for a flexible testing environment without the need for full size test chambers or containers.

## 1. INTRODUCTION

The performance of air conditioning and refrigeration systems has been the central focus of much research due to the large amount of energy consumed by vapor compression cycles (VCC) in industrial, commercial, residential, and automotive applications. Recently, research has focused on the development of advanced control algorithms to improve system wide performance (Hua *et al.*, 2009; Keir *et al.*, 2006; Lazzarin and Noro, 2008). Advanced control algorithms are typically developed in a simulation environment followed by validation through experimental testing to determine the actual performance.

While testing AC&R systems, it is imperative to determine how the system will cool a given container under certain ambient conditions and disturbances (i.e. transport refrigeration performance during changing ambient conditions). Current modeling and simulation techniques may be used to predict how a vapor compression cycle will cool a given container in a certain ambient condition (Li and Alleyne, 2009). These modeling techniques accurately predict the performance of AC&R systems; however, experimental validation is almost always required to determine the actual performance of the system.

The current method used to validate system performance is through testing AC&R units in environmental test chambers. The AC&R unit is attached to the container and placed in a test chamber which replicates the ambient conditions that may be experienced in the field. Environmental test chambers may be large enough to hold household refrigerators or may be much larger for applications such as transport refrigeration. Environmental test chambers are typically costly to install, operate and maintain while also consuming large amounts of space.

To mitigate these issues, hardware-in-the-loop load emulation has been invented to perform a task similar to that of the environmental test chamber. Hardware-in-the-loop (HIL) simulation is a common technique that has been used for many applications to reduce testing cost and provide a more flexible and controlled testing environment (Lu *et* *al.*, 2007; Isermann *et al.*, 1999). A HIL testing configuration is typically used as an intermediate or alternate step for testing a system in its actual environment.

Hardware-in-the-loop load emulation uses a model to account for the interactions between the environment and container instead of relying on a test chamber to replicate these interactions. An emulation unit places an equivalent load on the experimental system which is intended to replicate what the system would experience if subjected to such conditions in the field.

The remainder of this paper is organized as follows. Section 2 outlines the HIL load emulation framework. Section 3 provides a summary of the environmental load model development. Section 4 briefly details the load emulation control configuration. In Section 5 load emulation results are presented of a refrigeration system virtually cooling a truck environment. Section 6 summarizes the main contributions of this paper.

## 2. LOAD EMULATION FRAMEWORK

Vapor compression cycle hardware-in-the-loop load emulation is a novel technique that may experimentally simulate different environmental conditions and container sizes on a given system without the need to experimentally replicate such conditions in a test chamber. An environmental load model is used to characterize the container parameters, the environmental conditions, and system disturbances such as door openings. This model is implemented on-line during load emulation testing which allows for flexible testing of arbitrary environments and container parameters, similar to dynamometers for engine testing.

Hardware-in-the-loop load emulation is composed of two main components: an emulation unit and an environmental load model. The emulation unit is designed to allow for on-line control of the load on the AC&R unit under test. The emulation unit is attached to the evaporator and/or condenser during testing to control the inlet air temperature, or load on the system. In this study load emulation is considered on the evaporator side only, although a similar approach may be taken to emulate conditions on the condenser side. The inlet air temperature is controlled by mixing evaporator outlet air with ambient air through a mixing blade; see Figure 1. The angle, $\Theta$, of the mixing blade is modulated to precisely control the evaporator inlet air temperature, or system load. A refrigeration transport application will be used to illustrate load emulation in this study. Nevertheless, this technique may be applied to a variety of AC&R applications.

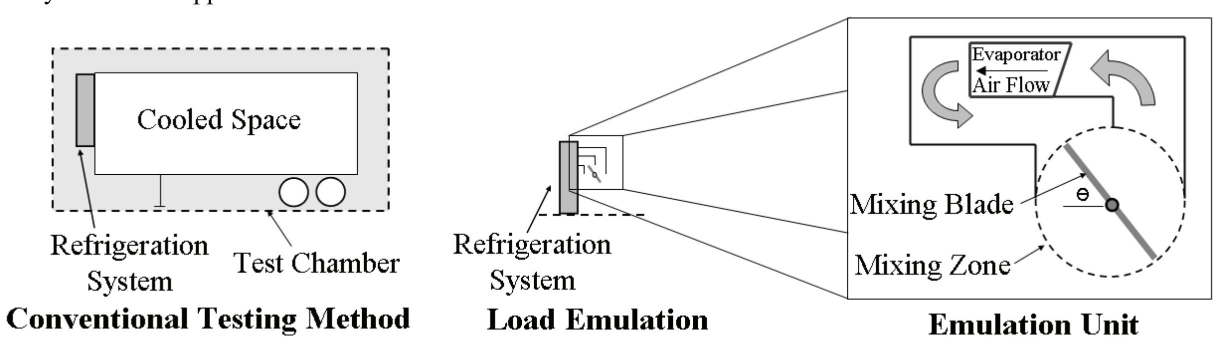


Figure 1: Hardware-in-the-Loop load emulation

## 3. ENVIRONMENTAL LOAD MODEL DEVELOPEMENT

The second key component for load emulation is the environmental load model. The environmental load model accounts for the container parameters, environmental conditions, and system disturbances. The interaction between the container and the VCC system is illustrated in Figure 2. The container, or cooled space, is coupled to the VCC system such that the cooled space input is supply air temperature from the VCC unit. Simultaneously, the VCC system input, the evaporator air inlet temperature, is the output of the cooled space, or output of the environmental load model.

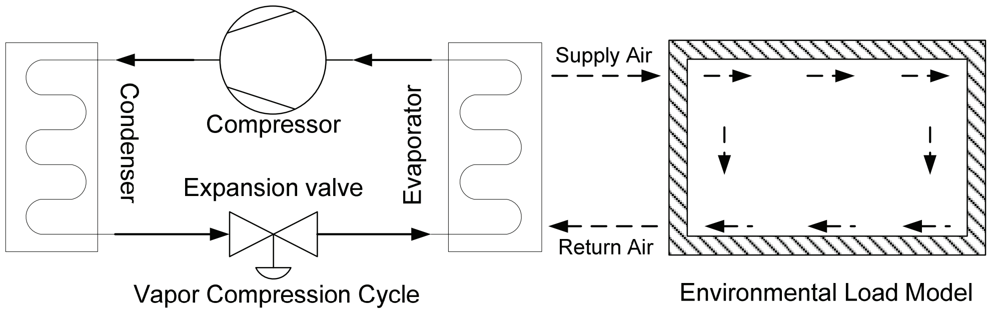


Figure 2: Schematic of the coupling between the VCC and cooled space

### 3.1 Environmental Load Model Description

Using the modeling framework presented in Li and Alleyne (2009), the environmental load model presented here accounts for the following important effects in refrigeration transport applications: (i) varying ambient conditions, including ambient temperature, solar radiation intensity, and wind speed; (ii) air infiltration; and (iii) door openings for product removal/loading. The environmental load model is developed based on a heat balance approach (ASHRAE, 2005). More precisely, the load model is formulated by calculating the conductive and convective heat balances for the space surfaces and space air. The major modeling assumptions are given below.

- Uniform air temperature with well-mixed air in the space;
- Uniform surface temperature for the space including its interior and exterior wall surface;
- One dimensional heat conduction through the walls of the space.

Three dynamic states, cooled space temperature $T_{space}$, interior surface temperature $T_{is}$ and exterior surface temperature $T_{es}$, are defined to describe the load model dynamics, as shown in Equation (1). The dynamic state derivative equations are given in Equations (2)-(4)

$$x = \begin{bmatrix} T_{space} & T_{is} & T_{es} \end{bmatrix}^T \tag{1}$$

$$\frac{dT_{space}}{dt} = \frac{\dot{Q}_{inconv} + \dot{Q}_{inf} + \dot{Q}_{door} - \dot{Q}_{vcc}}{(MC)_{air}} \tag{2}$$

$$\frac{dT_{is}}{dt} = \frac{\dot{Q}_{cond} - \dot{Q}_{inconv}}{(MC)_{wall}} \tag{3}$$

$$\frac{dT_{es}}{dt} = \frac{\dot{Q}_{solar} + \dot{Q}_{outconv} - \dot{Q}_{cond}}{(MC)_{wall}} \tag{4}$$

where the solar load $\dot{Q}_{solar}$, the air infiltration load $\dot{Q}_{inf}$, and the VCC system capacity $\dot{Q}_{vcc}$ are computed from Equations (5)-(7). The sensible and latent refrigeration load, $\dot{Q}_{door}$, from door openings is calculated by Equation (8) (ASHRAE, 2002). The convection and conduction load information, including $\dot{Q}_{outconv}$, $\dot{Q}_{inconv}$ and $\dot{Q}_{cond}$, can be found in Li and Alleyne (2009). The major environmental load model parameters used for this study are listed in Table 1.

$$\dot{Q}_{solar} = \alpha I_{solar\_radiation} \tag{5}$$

$$\dot{Q}_{inf} = V_{space} \rho_{air} c_{air} (T_{amb} - T_{space})(ACH) \tag{6}$$

$$\dot{Q}_{vcc} = \dot{m}_{air} c_{air} (T_{space} - T_{supply}) \tag{7}$$

$$\dot{Q}_{door} = 0.221 D (h_{amb} - h_{air}) \rho_{air} (1 - \frac{\rho_{amb}}{\rho_{air}})^{0.5} (gH)^{0.5} F \tag{8}$$

Table 1: Environmental load model parameters

| Variable | Definition | Value | Unit |
|---|---|---|---|
| $(MC)_{wall}$ | Wall thermal capacity | 100 | kJ-C$^{-1}$ |
| $(MC)_{air}$ | Air thermal capacity | 20 | kJ-C$^{-1}$ |
| $(UA)_{wall}$ | Lumped heat transfer coefficient | 0.06 | kW-C$^{-1}$ |
| $A_{space}$ | Space surface area | 82.43 | m$^2$ |
| $V_{space}$ | Space volume | 38.62 | m$^3$ |
| $\alpha$ | Absorptivity to solar radiation intensity | 0.12 | |
| $ACH$ | Air changes per hour | 0 | |

### 3.2 Environmental Load Model Validation

The environmental load model is implemented in Thermosys (Rasmussen, 2005), and the model validation scenario involves a temperature pull-down and control test along with door-opening events for the enclosed space. The model is validated against data collected from the cooling of an actual commercial truck environment at a testing facility. The test procedure can be described as:

- Pull-down the enclosed container air temperature from ambient temperature to a given set-point using the refrigeration system;
- Run the compressor in an on-off cycling pattern to maintain the space temperature during which the system disturbance of door openings is introduced.

The environmental load model inputs, including ambient air temperature, supply air flow rate, supply air temperature, and door-opening signals, are given in Figure 3. The model validation is presented in the final plot in Figure 3 where the space air temperature from test data is compared to the environmental load model output.

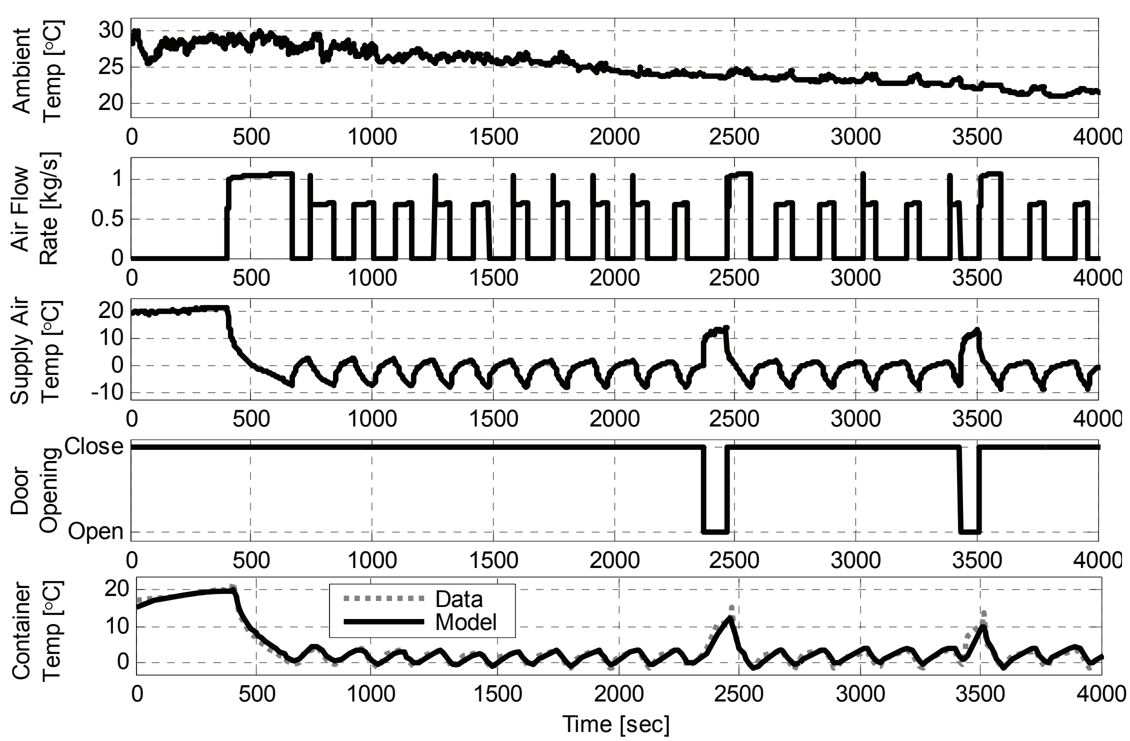


Figure 3: Environmental load model inputs and validation

### 3.3 On-Line Load Emulation Simulation

The environmental load model is implemented on-line during load emulation testing to determine how the experimental system would cool the virtual container by using sensor data from the system. The evaporator outlet air temperature, or supply temperature to the virtual container, is measured on-line and provided to the environmental load model. The ambient conditions and disturbances may be changed on-line to represent dynamic conditions experienced in the field. The return air temperature output of the model captures the virtual load on the system. This output is the input to the emulation unit which places this load on the system under test through the mixing blade controller; see Figure 4.

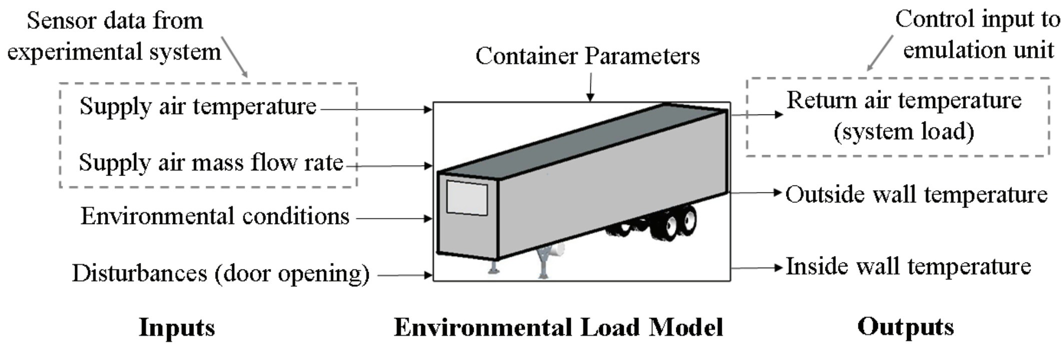


Figure 4: Environmental load simulation configuration

## 4. LOAD EMULATION CONTROL LOOP

The load emulation control loop is shown in Figure 5 where sensor data is provided to the on-line simulation along with environmental conditions and container parameters. The output of the on-line simulation is the desired load on the AC&R system. The mixing blade controller then tracks this desired load, equivalent to the input air temperature, on the experimental system through modulation of the mixing blade angle.

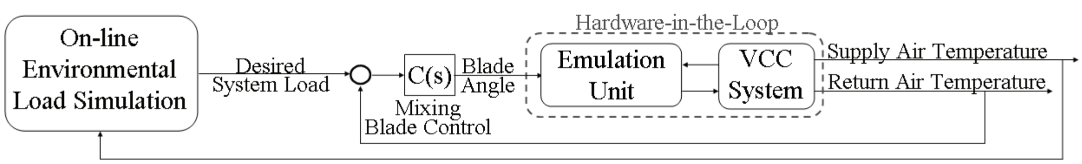


Figure 5: Hardware-in-the-loop load emulation control structure

## 5. LOAD EMULATION RESULTS

This section provides load emulation results from an air conditioning test bed virtually cooling a large truck environment. An emulation unit is attached to the evaporator of the air conditioning test bed and the system is configured to virtually cool the truck environment with on-off control through load emulation; see Figure 6. A more detailed description of the air conditioning test bed can be found in Rasmussen (2005).

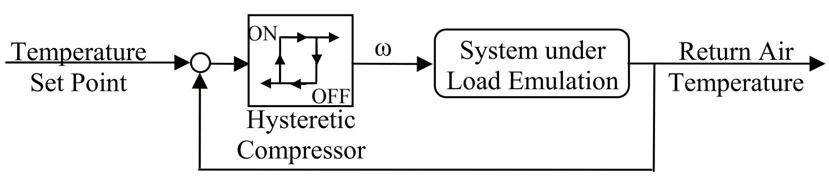


Figure 6: On-off container temperature control diagram

Figure 7 presents load emulation results from the air conditioning test bed virtually cooling a truck environment during a cloudy day in an ambient temperature of 25°C. The virtual container temperature begins at 25°C and is pulled down to the temperature set point of 16.5$\pm$1.5°C where this temperature is maintained by on-off compressor cycling. The evaporator inlet air temperature tracks the virtual container temperature through the mixing blade controller which modulates the blade angle. As the container temperature is pulled down, the blade angle slowly decreases to meet the inlet air temperature set point. In order to track the virtual container temperature, the blade angle has large variations during the on-off cycling due to variable sensitivity between blade angle and inlet temperature. This data is extremely useful in determining the performance of the AC&R system in terms of cool ing rate, compressor cycling frequency, and energy consumption. Load emulation may also be used in determining the performance of control loops such as the capacity or superheat control loop.

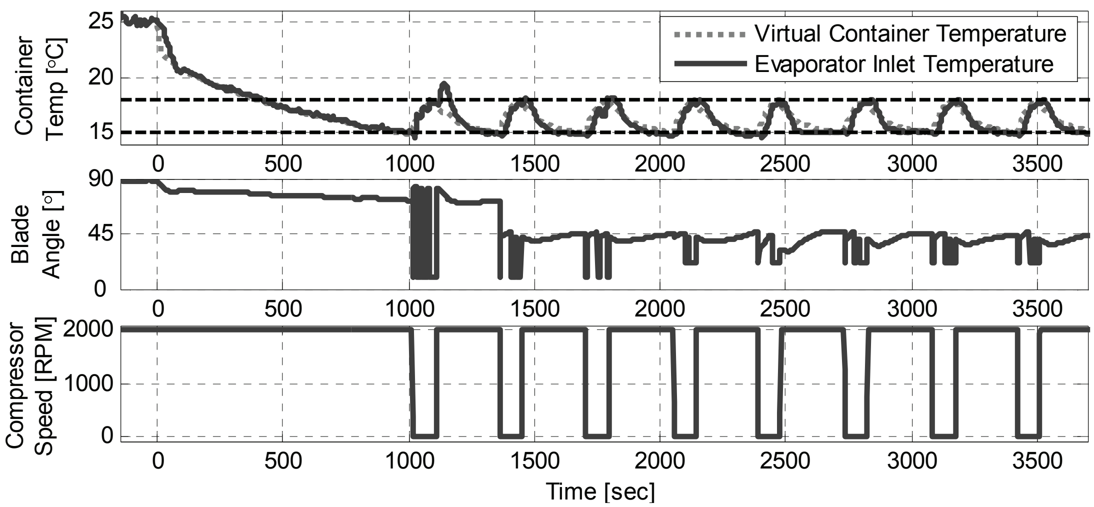


Figure 7: AC&R test bed virtually cooling a truck environment with on-off control through load emulation

To illustrate the flexibility of testing systems with load emulation, Figure 8 presents results with door opening disturbances. The door opening event represents the disturbance to the system when the truck environment is exposed to ambient air during the transfer of goods in/out of the cooled space. This disturbance may be used to investigate how a controller will respond to large temperature deviations or how much additional energy is consumed during each door opening event.

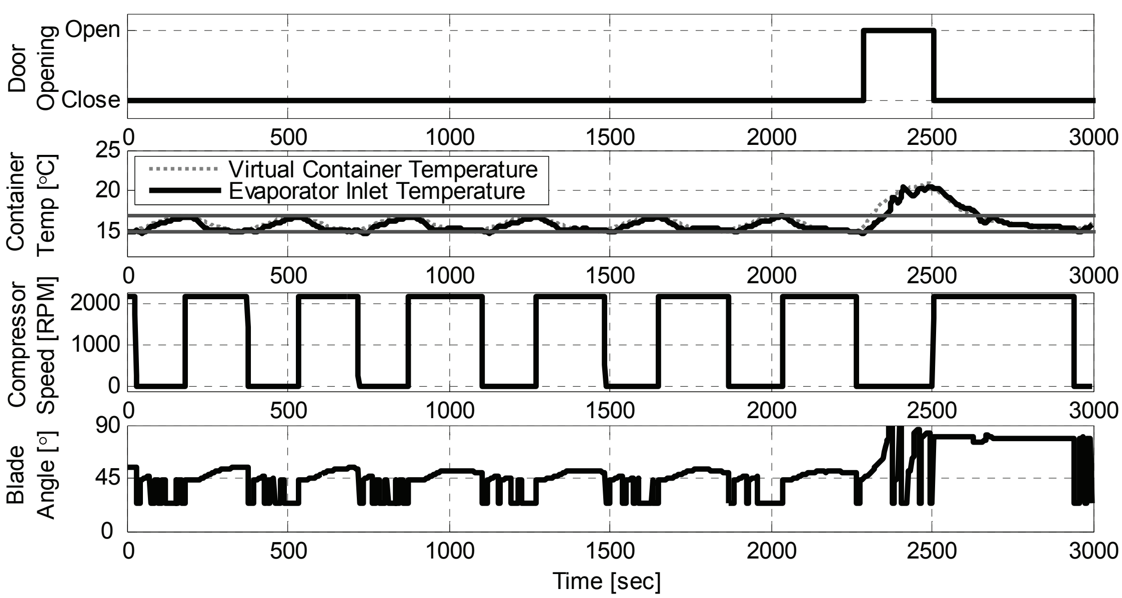


Figure 8: Door opening disturbance through load emulation

Hardware-in-the-loop load emulation may also be used to analyze the performance of variable speed systems. In this case a PID controller is used to regulate compressor speed to meet the temperature set point; see Figure 9.

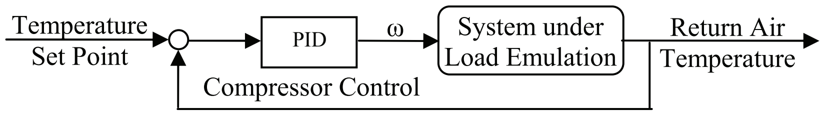


Figure 9: Variable speed container temperature control diagram

Figure 10 presents results of the air conditioning test bed in a variable speed configuration virtually cooling a truck environment on a cloudy day in an ambient temperature of 25°C. The virtual container temperature begins at 25°C and is pulled down to the set point of 16.5°C. During this time the temperature control loop varies the compressor speed to meet the temperature set point. Hardware-in-the-loop load emulation allows performance characteristics to be identified without having to place the air conditioning unit and real container within a test chamber.

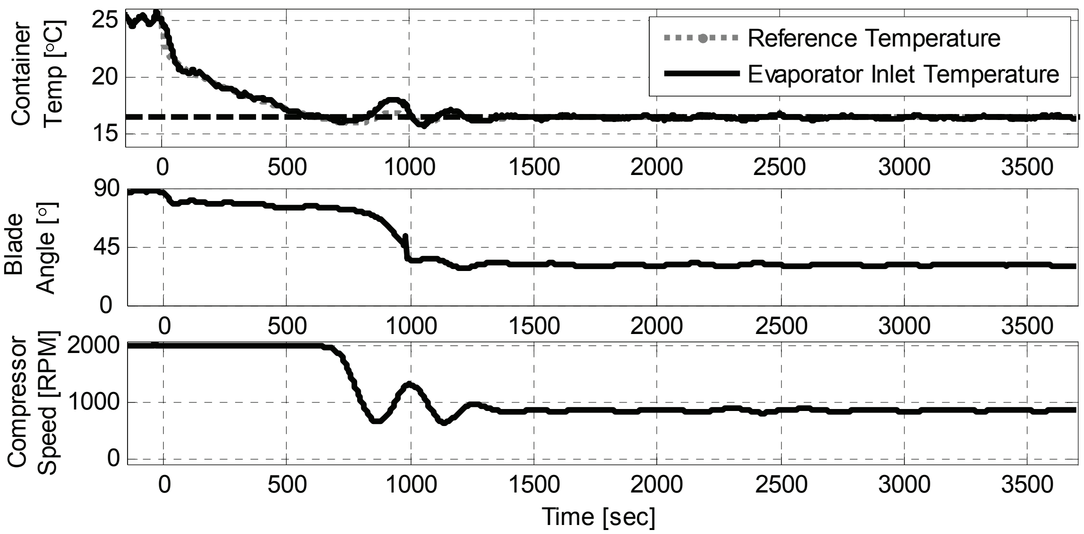


Figure 10: AC&R test bed virtually cooling a truck environment with variable speed control through load emulation

Figure 11 further highlights the flexibility of load emulation testing by subjecting the system to varying ambient conditions. The decrease in ambient temperature causes the virtual load temperature to deviate from the set point which drives the temperature control loop to decrease the compressor speed to meet set point requirements. These emulation results allow for performance evaluation that would normally require large test chambers.

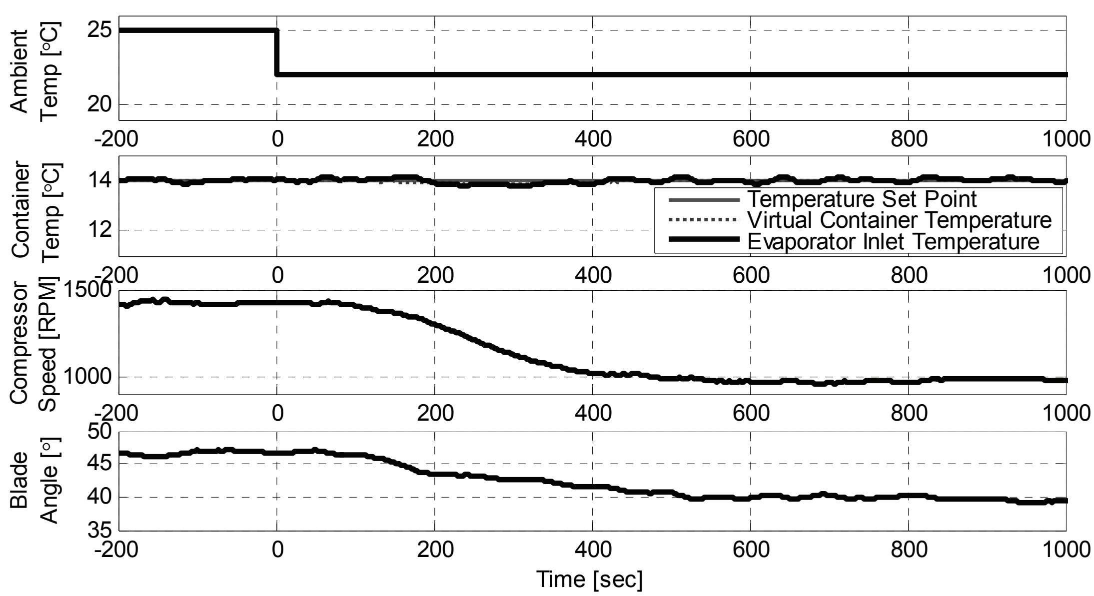


Figure 11: Change in ambient temperature during operation through load emulation

## 6. CONCLUSIONS

Hardware-in-the-loop load emulation has been shown to provide a flexible testing environment for air conditioning and refrigeration systems. This method provides an alternate solution to full scale testing in a test chamber which is both a costly and space consuming method of testing. Instead, an environmental load model accounts for the interactions between the AC&R unit, the container, and the surrounding environment. Hardware-in-the-loop load emulation provides a framework which may be used to determine the performance of AC&R systems or control algorithms during disturbances normally experienced in the field. Future work may investigate alternate blade designs, such as a shaped or curved blade, which may reduce the non-linear inlet temperature dynamics to reduce blade actuation during on-off system load emulation and further improve load tracking.

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