

A Sensor for Estimating the Liquid Mass Fraction of the Refrigerant Exiting an Evaporator

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James Solberg, Norman R. Miller, and Predrag Hrnjak

ABSTRACT

A traditional method of controlling evaporator superheat in a vapor compression air conditioning system is the thermostatic expansion valve (TXV). Such systems are often used in automotive applications. The TXV depends on superheat to adjust the valve opening. Unfortunately, any amount of superheat causes that evaporator to operate at reduced capacity due to dramatically lower heat transfer coefficients in the superheated region. In addition, oil circulation back to the compressor is impeded. The cold lubricant almost devoid of dissolved refrigerant is quite viscous and clings to the evaporator walls. A system that could control an air conditioner to operate with no superheat would either decrease the size of its existing evaporator while maintaining the same capacity, or potentially increase its capacity with its original evaporator. Also, oil circulation back to the compressor would be improved. To operate at this two-phase evaporator exit condition a feedback sensor would have to quantify the quality of liquid mass fraction (when the exit stream is a mixture of droplets and superheated vapor) of the refrigerant exiting the evaporator.

INTRODUCTION

One of the most common control schemes for a vapor compression air conditioning system is the use of a thermostatic expansion valve (TXV). TXV systems use a remote thermal bulb at the exit of the evaporator. This bulb causes the TXV to open and close in response to changes in superheat of the refrigerant at the evaporator outlet. If the temperature of the refrigerant increases rapidly, as would be the case when the heat load was suddenly increased, the power element would open the valve and admit more liquid refrigerant to the evaporator. Once in the evaporator, the liquid refrigerant absorbs heat by changing state from liquid to gas. By the time it leaves the evaporator, the gaseous refrigerant has been superheated a few degrees.

By allowing the evaporator to operate with some finite superheat at its exit, some portion of the evaporator will have only vapor flowing through it (no liquid). This situation decreases the refrigerant-side heat transfer. This portion of the evaporator is not able to vaporize refrigerant, and is only able to transfer heat via the sensible heating of the refrigerant. This process can reduce the capacity of the evaporator.

Any control scheme that uses superheat as its control signal (e.g. TXV systems) must have some finite superheat. Such a system is unable to control the plant to operate in a regime of saturated liquid/vapor at the exit of the evaporator. The minimum amount of superheat that such a system can use and maintain stability is dependent on the method of measuring the superheat.

The difficulty of a temperature measurement is in part due to the non-equilibrium flow of refrigerant as it exits the evaporator only slightly superheated. The flow is said to be non-equilibrium because saturated liquid droplets are entrained in superheated vapor. There is just not enough time for the liquid to vaporize and reach equilibrium. This phenomenon can be attributed to maldistribution of liquid/vapor refrigerant throughout the evaporator and to the nature of two-phase flow [1,2,3,4]. The saturated liquid droplets in superheated vapor flow regime cause temperature transducers to exhibit large variances.

In evaporators with imperfect distribution exit streams could be a mixture of superheated vapor and droplets. Some channels or circuits that are thermally overloaded have superheated vapor at the exit, while others where thermal loads are not sufficient to evaporate all liquid that enters will have some droplets at the exit. The mixture of these streams is in thermal non-equilibrium. After sufficient time (or length of pipe) droplets could completely evaporate, reducing superheat. But if the sensible heat available in the superheated vapor is not enough energy to vaporize all droplets, then the exit is in the quality region. Liquid-mass-fraction (LMF), which is the mass of liquid in vapor of any state, is one parameter to describe the state at the evaporator exit, as described in Shannon, Hrnjak, and Leicht [12].

A temperature transducer measuring the temperature of refrigerant in this non-equilibrium flow regime can read the saturation temperature (if a liquid droplet is on the transducer), or can read the temperature of the superheated vapor (which may not be constant), or can read any value in between. A large variance in a control signal (e.g. superheat) can cause a controller to hunt. Since the non-equilibrium flow has superheated vapor along with liquid droplets, quality cannot be used to correctly describe the state of the refrigerant.

Some of the best TXV systems are only able to maintain stable operation with a minimum of about 5 degrees Fahrenheit. But, a patent does exist for a transducer that appears to function in a similar fashion as the device described in this paper. Patent number 2219661 was granted on May 13th, 1992 to York International Ltd by the Comptroller-General of Patents, Designs and Trade Marks, United Kingdom Patent Office. In addition several companies are currently pursuing a prototype commercial transducer. However to the authors' knowledge no results for this class of sensors has appeared in the open literature.

THE SENSOR

A sensor that could estimate the liquid mass fraction (LMF) at the exit of the evaporator could be used in the feedback loop of a control scheme that would maintain the refrigerant at a constant LMF. Liquid mass fraction (LMF) is the ratio of the mass of liquid to the total mass of the fluid, whether or not it is in equilibrium.

PREVIOUS WORK

One of the early studies of superheat stability was carried out at the University of Illinois by Wedekind and Stoeker in the 1970's [1, 2, 3]. The project addressed the stability of the location of the last evaporated droplet in a straight, electrically heated, glass tube. It was found that the location of the last evaporated droplet (the end of the two-phase region) is a stochastic function and the distribution was determined. Some years ago Barnhart and Peters studied stability at the exit of a single glass tube serpentine evaporator [4]. They observed the same phenomena described by Stoeker and determined that most of the instabilities at the exit were generated far upstream (also see [13]).

In another project the unsteadiness of the exit temperature signal was used as an identifier of "stable" operation [12]. The idea of using the variance of the temperature signal at the exit of the evaporator for better flow was developed.

That idea was further developed in a project whose objective was to develop a micro electromechanical system (MEMS) sensor that would do a better job of sensing droplets at the evaporator exit than a thermocouple. A new MEMS sensor (a heated resistance temperature detector RTD) was developed.

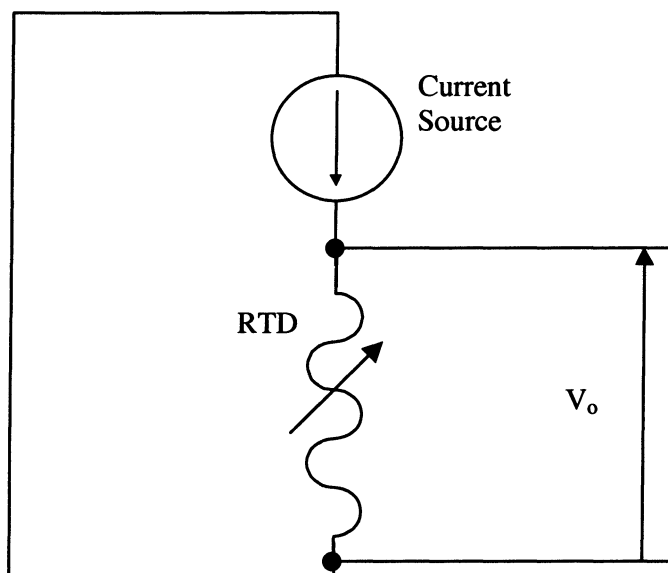


Figure 1 Circuit diagram of MEMS RTD electronic circuitry

The MEMS RTD was driven by a current source and the voltage drop across the sensor was the measured variable (see Figure 1). This voltage is a function of the temperature of the sensor. Notice that this device is essentially an uncompensated hot film anemometer (see page 90 of [5]). Hot wire anemometers have been used to detect droplets entrained in gases (page 181 of [5]). The sensor is cooled as each droplet strikes the hot sensor and is evaporated.

FUNCTIONALITY OF SENSOR

An interesting variation is the use of constant resistance transducer control (see Figure 2). This variation of the circuit tries to keep the resistance of the RTD equal to R_{set} . The voltage V_o is then directly proportional to the current needed to achieve this condition. The power removed by heat transfer into the refrigerant stream is, of course, the square of the current flowing through the RTD times the RTD resistance (or R_{set}).

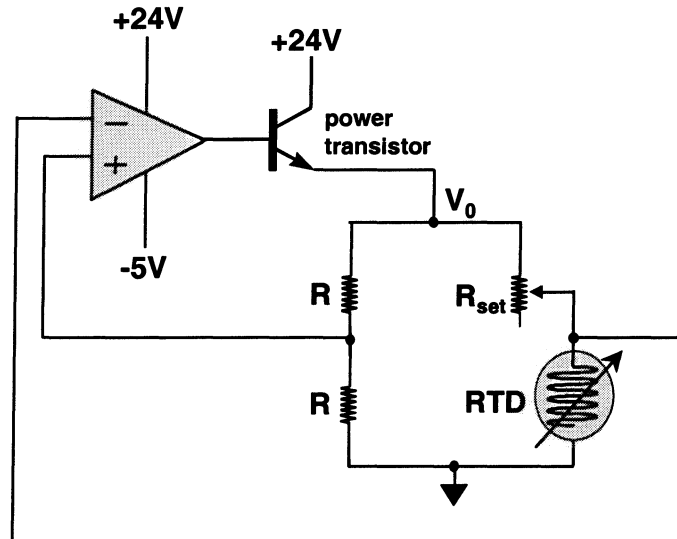


Figure 2 Constant sensor resistance control circuit

This circuit uses an operational amplifier as the medium for feedback. The op-amp uses the feedback to maintain its inputs at constant voltage while drawing very little current. This is what forces the resistance of the RTD to be equal to the resistance of R_{set} . Traditionally, an RTD is used to measure temperature by measuring the resistance of the RTD as it changes with temperature. But, this circuit forces the resistance of the RTD to be equal to R_{set} . The circuit compensates by heating up the RTD until the resistance (and thus the temperature) of the RTD is equal to R_{set} .

Such a system has a much wider bandwidth (that is, it will respond to much higher rate variations in heat flux). The reason is as follows. Constant current excitation requires that the transducer temperature changes for any change in transducer resistance and hence signal to be observed. This is an inherently slow (relatively long time constant) process dominated by the thermal capacity of the transducer body. Constant resistance operation implies that the circuitry varies the transducer current so that the transducer stays at a constant resistance and hence a constant temperature. The thermal energy stored in the transducer body does not change. This technique is used with hot wire anemometers and provides very broadband performance (bandwidths up to 0.5 MHz). The technique also has the advantage of protecting the sensor from overheating.

The circuit maintains the voltage drop across the RTD equal to half of V_o . And since the R_{set} is equal to the resistance of the RTD, the power dissipated through the RTD can be determined. By measuring the temperature of the refrigerant passing over the sensor and inferring the temperature at the surface of the RTD from R_{set} , the difference of these temperatures can be found. This paper refers to this temperature difference as overheat. The overheat represents the driving potential that allows power to be dissipated through the sensor.

The ratio of the power dissipated to this temperature difference can be interpreted as "the surface-to-free-stream thermal conductance" between the RTD and refrigerant. It is essentially the convection heat

transfer coefficient multiplied by the effective surface area (hA). This surface-to-free-stream thermal conductance (hA) does not depend on the effective surface area of the sensor because neither the geometry nor the orientation of the sensor varies. This hA parameter is particularly sensitive in the high quality/low superheat region (low LMF). As the LMF of a fluid increases, so does its hA .

As a droplet of saturated liquid refrigerant clings to the surface of the RTD, the RTD circuitry will do what it can to raise its temperature back its set point (which is determined by R_{set}). To do this the RTD must transfer enough energy to the refrigerant to overcome its latent heat of vaporization. As the LMF of the fluid decreases, less energy is dissipated through the RTD. When the fluid becomes all vapor, all of the energy flux through the RTD goes to sensible heat that is needed to raise the temperature of the RTD to its set point.

Two testing facilities were used to collect data. The first facility was used to demonstrate relationships between the sensor's power dissipation, overheat, and the quality of refrigerant flowing over the sensor. The second facility was used to show how the sensor could be used to predict the performance of an air conditioning system.

EXPERIMENTAL DYNAMICS

The first set of experiments were conducted to investigate relationships between the sensor's power dissipation, overheat, and the quality of refrigerant flowing over the sensor.

EXPERIMENTAL FACILITY

An existing refrigeration system was used, for the purposes of this study, in the Laboratory for Plate Heat Exchangers at the University of Illinois in Urbana-Champaign. It is designed to simulate evaporator operating conditions typical of water chillers of less than 60 ton (210 kW) capacity using plate heat exchangers for evaporation. The facility consists of three main parts: the refrigerant loop, the water loop, and the evaporator exit test section. A detailed description is given in [12].

The refrigeration loop contains the four necessary elements of a vapor-compression cycle refrigeration system: compressor, condenser, expansion device, and evaporator. In addition, there is a receiving tank for collecting high pressure liquid from the condenser, a liquid subcooler, and instrumentation for monitoring process conditions. The system schematic is shown in Figure 3, where solid lines represent refrigerant piping, and dashed lines represent water piping. The compressor is a Copeland model ZR61K2 hermetically sealed scroll compressor. The refrigerant is R22. Mineral oil circulates through the entire flow loop, including the test section, and is necessary to lubricate the compressor. A common problem in these types of systems is oil accumulation in the evaporator when operating at high superheats. This reduces evaporator capacity, and could influence refrigerant side maldistribution.

The evaporator is a SWEP model B15×40 3-ton (10.5 kW) capacity parallel plate heat exchanger. It consists of 19 refrigerant passages and 20 water passages operating in a counter-flow configuration. The plates have chevron style contours to enhance heat transfer. Two-phase refrigerant enters at the bottom of the evaporator, evaporates vertically through the plates, and exits at the topside of the evaporator. The heat load to the evaporator is supplied by water from the water reservoir. Thermocouples located at the entrance and exit of the refrigerant and water streams monitor process conditions.

A 12 kW Watlow water circulation heater provides the thermal load on the evaporator. Hot water from the condenser can also be redirected into the evaporator if desired.

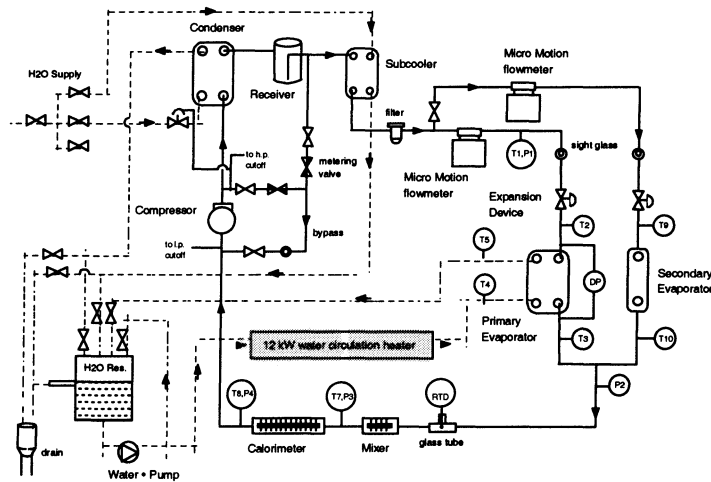


Figure 3 The refrigeration loop used to determine the sensor's dynamics

The test section consists of the RTD sensor, a glass tube for flow visualization, a static mixer, a calorimeter, and several thermocouples and pressure transducers for monitoring flow conditions. Refrigerant exits the evaporator before passing over the RTD sensor. Then it passes through a mixer in order to ensure the state of the refrigerant is either pure superheated vapor or saturated vapor/liquid. If the refrigerant is two-phase, then a known amount of energy is put into the refrigerant as it passes through the calorimeter. After all the liquid is vaporized temperature and pressure measurements are taken to estimate the refrigerant's enthalpy. The enthalpy entering the calorimeter is equal to the enthalpy of the refrigerant exiting the calorimeter minus the energy provided by the electric heaters inside the calorimeter. Once the enthalpy of the refrigerant entering the calorimeter is known, its quality can be estimated.

DATA COLLECTION

In order for the sensor to be useful some relationship between refrigerant quality, overheat (temperature difference), and power dissipated through the sensor needs to be developed. Quality is determined from the enthalpy of the refrigerant entering the calorimeter. Overheat is the difference between the temperature of the RTD and the temperature of the refrigerant. The power dissipated through the RTD is determined by the square of the RTD's voltage drop divided by its resistance.

Once it was established that hA is constant for a given quality, the next task was to develop a relationship between quality and hA . Figure 5 shows the results of an experiment where the RTD sensor was subjected to various qualities. Quality was measured by using a calorimeter in the method described earlier.

As quality decreases more and more liquid droplets hit the sensor. This demands more power to be dissipated through the sensor in order for the sensor to maintain its constant temperature. At the same time the temperature of the refrigerant is fixed at its saturation temperature. So the ratio of the dissipated power to the overheat (hA) increases as quality decreases. This theory is supported by the data shown in figure 5.

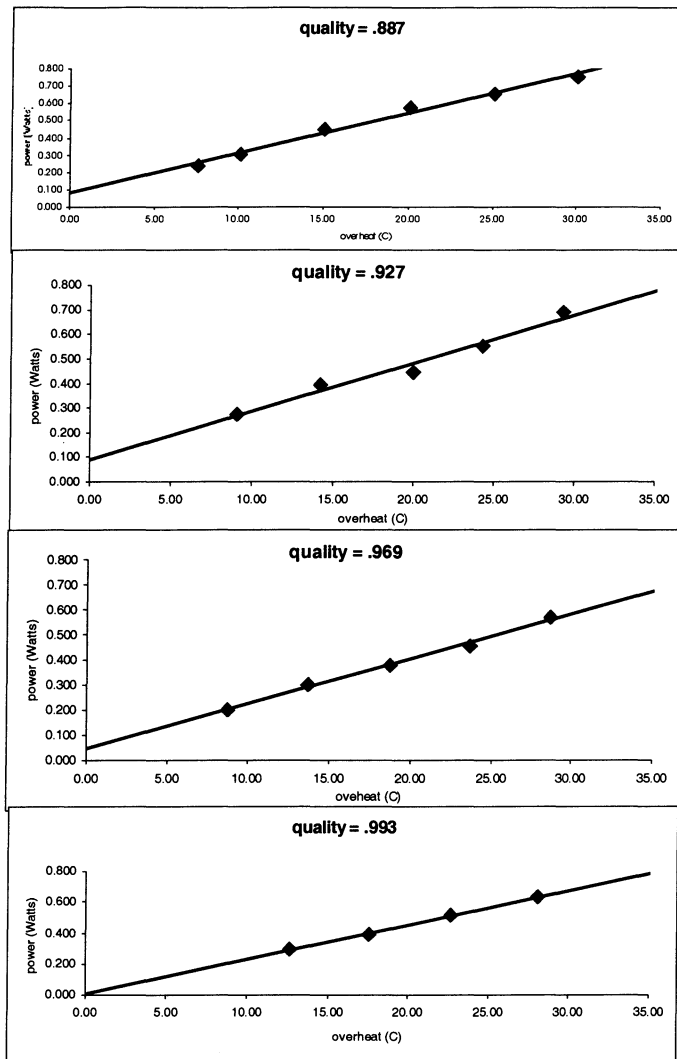


Figure 4 The power dissipated through the sensor as a function of overheat while the quality of refrigerant over the sensor is held constant. The slope represents the hA parameter. R_{set} in figure 2 was varied to change the overheat.

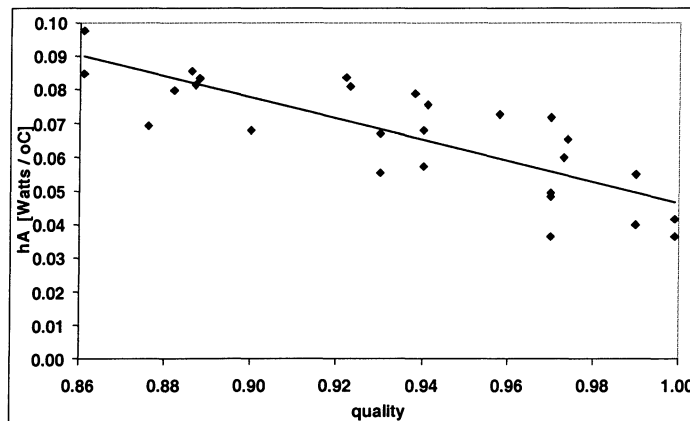


Figure 5 The the surface-to-free-stream thermal conductance (hA) as an estimate of refrigerant quality.

Experiments were conducted that would demonstrate the dependence of sensor power and overheat while the quality was held constant. Figure 4 shows the results of such experiments. The results show that power dissipated is a linear function of overheat (the temperature difference between the sensor and the refrigerant). The data agrees with the convection heat transfer model which takes the form:

$$q = h \cdot A \cdot (T_s - T_\infty) \quad (\text{eq. 1})$$

T_s is the fixed temperature at the surface of the RTD. T_∞ is the temperature of the free-stream refrigerant passing over the sensor. The power dissipated can be modeled as the energy transfer q . The overheat in the system is analogous to $(T_s - T_\infty)$. And the slope of the line represents hA . hA is the product of the convection heat transfer coefficient and the effective surface area.

One reason for the significant scatter in the data may be due to the inaccuracies in measuring quality. Quality at the exit of the evaporator was inferred indirectly. What was actually estimated was the quality of refrigerant entering the calorimeter after it had passed through a mixer. Implicit to the data used to construct figure 5 are the assumptions that the refrigerant passing over the sensor was saturated liquid/vapor and that none of the refrigerant changed phase between the sensor and the entrance of the calorimeter. Neither one of these assumptions is necessarily true.

EXPERIMENTAL PERFORMANCE

Once it was established that the sensor could predict the heat transfer from refrigerant (and from that measurement infer a quality), data was taken that would help explore how this sensor could improve the performance of a vapor compression system. One possible application for the sensor would be to use it as the feedback signal in a control scheme that would maintain the refrigerant at the exit of the evaporator at saturated liquid/vapor.

EXPERIMENTAL FACILITY

A versatile mobile air conditioning experimental facility capable of testing a/c systems under transient and steady-state operation was utilized in the investigations described in this document. Collins [6], Rubio-Quero [7] and Weston [8] present detailed test facility descriptions and construction information. The evaporator and condenser are housed in separate air loops. The blower in the evaporator air loop is capable of producing volumetric flow rates equal to that of a passenger compartment fan. The blower in the condenser air loop is capable of producing a high volumetric flow rate to replicate the radiator fan and ram-air effect associated with vehicle motion. The refrigerant loop contains factory standard automotive air conditioning components for a 1994 Ford Crown Victoria. Figure 6 illustrates a schematic of the test facility. The letters T, P, and RH found in Figure 6 represent instrumentation for temperature, pressure, and relative humidity measurement, respectively. An Allen Bradley programmable logic controller can be used to control the evaporator and condenser blower speeds, compressor RPM, compressor clutch and an electronic expansion valve (EEV).

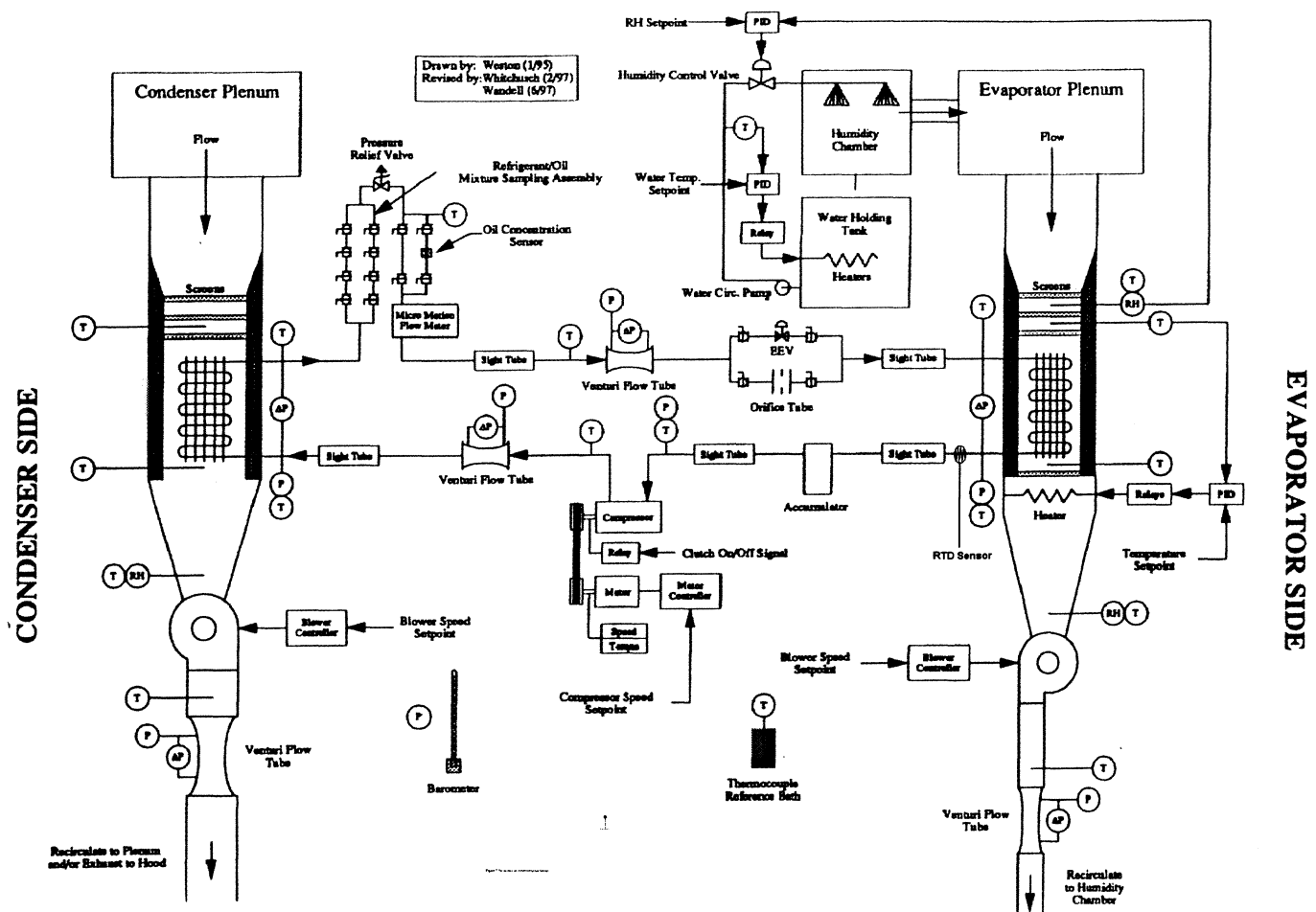


Figure 6 The mobile air conditioning test facility

EXPERIMENTAL PROCEDURE

The following data was collected to demonstrate the sensor's ability to estimate certain system parameters. The test facility was subjected to various operating conditions typical of automotive air conditioners under heavy thermal load. Air-side inlet conditions to both the evaporator and condenser were held constant. Air passing over the evaporator was at 83 °F, 31% relative humidity, and 285 cubic feet per minute (cfm).

While the air-side inlet conditions were constant, the refrigerant-side inlet conditions into the evaporator were throttled with a Sporlan SEI2 stepper-motor-driven electronic expansion valve (EEV). The EEV has a 2 ton nominal capacity. The valve has an opening stroke of 0.125 in. and 1532 steps of control. The valve was sized based on the evaporator capacity, evaporating temperature, liquid-line refrigerant temperature, and valve pressure drop. Details of the EEV characteristics can be found in Wandell [9].

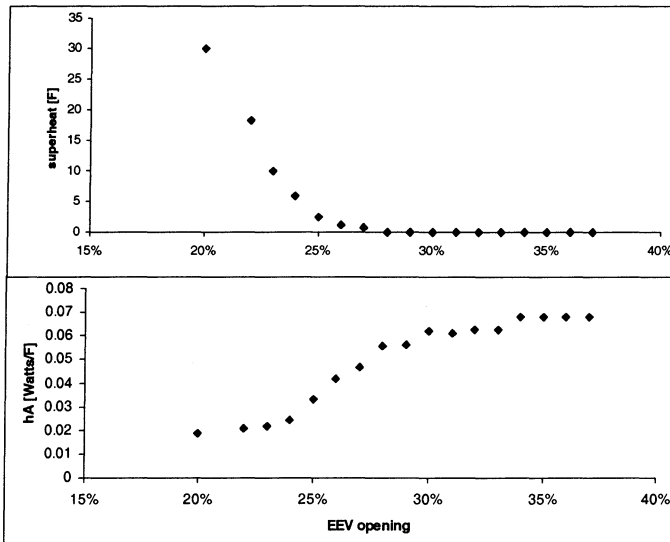


Figure 7 superheat (top) and hA (bottom) as a function of EEV opening

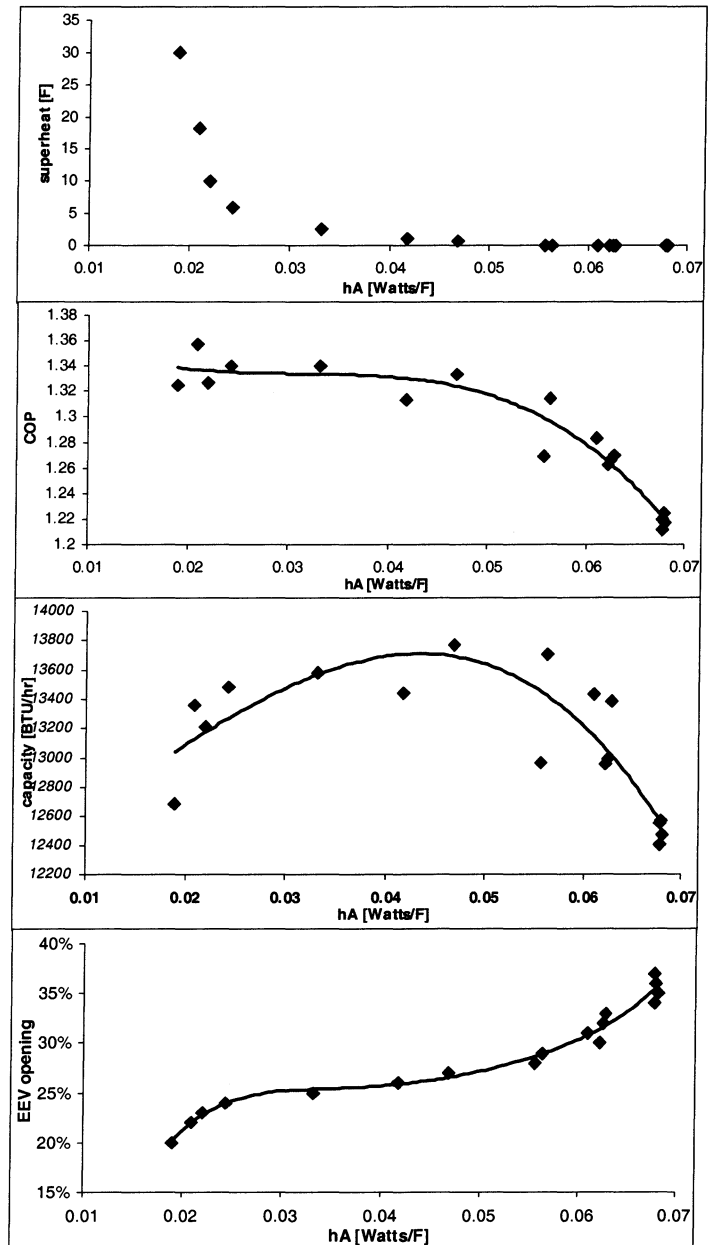


Figure 8 The ability of the parameter hA to predict superheat (top), COP (second), capacity (third), and EEV opening (bottom). Points represent individual data points, and solids lines are a least squares fit of a 3rd order polynomial.

For each data point the opening of the EEV was set, then the system was allowed to settle to a steady-state value before the data was recorded. Once the data was collected, only the opening of the EEV was changed before the next data point was collected.

EXPERIMENTAL RESULTS

Figure 7 shows how the surface-to-free-stream thermal conductance (hA) and degree of superheat varies with the opening of the EEV. Superheat is defined here as the difference between the temperature of the refrigerant and its saturation temperature for its pressure. When the valve is relatively closed (20%), there is significant superheat. hA is not affected much by the degree of superheat. That is because there was an insignificant change in refrigerant vapor velocity to affect convection on the sensor surface.

Once liquid droplets appear, the sensor must dissipate more power to compensate for the additional latent heat. Saturated liquid droplets appear in superheated vapor at around 15 °F superheat. At this point opening the EEV will allow more liquid to pass over the sensor, thus increasing hA .

Opening the valve even further brings the refrigerant into a regime of saturated liquid/vapor (true quality). These are the conditions under which this sensor can effectively operate and traditional temperature sensors cannot. Increasing the opening of the EEV even further will saturate the sensor at some quality. The actual heat transfer coefficient of the fluid probably does not actually maintain a constant value for increasing quality. The apparent leveling off is probably saturation of the sensor. Too much liquid is impinging the sensor. The sensor is not able to provide enough power to heat and vaporize the liquid.

It is apparent from figure 7 that the range of sensitivity of this sensor is in the low LMF region and high quality. This would be the range of operation where the sensor would be most useful.

Figure 8 demonstrates the sensor's ability to predict system performance. COP is relatively flat over regions of high superheat (low hA). It does not significantly drop off until well into the two-phase region (no superheat and high hA). According to this data, the capacity peaks out somewhere around 0.04 and 0.05 Watts/°F. This is the region where the system has its maximum cooling power for the set of operation conditions. This region corresponds to little to no superheat.

Capacity measurements are taken from the difference in enthalpies between the air going into the evaporator and the air coming out. Volumetric flow rates are measured using a venturi on the air loop on the evaporator side. Relative humidity and temperature measurements are taken for the air going in and coming out of the evaporator.

ANALYSIS OF RESULTS

The data presented in figures 4 and 5 along with the discussion presented in this paper demonstrate the ability of this sensor to predict the quality of refrigerant for that set of unique operating conditions. The data presented in this paper is specific to the facilities and conditions described in this paper. Not enough data has been taken to generalize the sensor's behavior. The sensor's behavior can significantly change if it is used in another system. Parameters such as sensor orientation, distance to the evaporator, refrigerant type, pipe cross-section, and evaporator type, all of which were held relatively constant for each set of experiments, would create inconsistent results. All of these parameters mentioned would change the convection heat transfer coefficient between the refrigerant and the RTD. This is the heat transfer coefficient being estimated to predict quality. But, in general these same parameters will remain unchanged for a given system.

The refrigerant must be well mixed as it passes over the sensor in order for the results to be valid. The liquid droplets need to be relatively distributed throughout the cross-section of the pipe. This ensures that the sensor is getting a representative sample. In reality a small portion of the refrigerant is being carried in oil-refrigerant mixture that flows attached to the tube walls. The sensor cannot detect that portion of the flow. Our experience demonstrates that the sensor should be placed very near the evaporator exit, preferably in a vertical section of tube.

The primary objective of this study was to construct and characterize a sensor that could be used in a control scheme with feedback that would improve the effectiveness of an air conditioning system. When operating an air conditioner under a high thermal load, the control objective might be to maximize capacity. For automotive applications this would mean minimizing pull-down time by getting the most cooling power for a given evaporator. According to the data presented in figure 8, this would correspond

to an hA of about 0.045 Watts/ $^{\circ}$ F. This condition also corresponds to very little or no superheat. By using the sensor presented in this paper a controller can be constructed to regulate the system at this condition.

The same system cannot use the traditional estimate of temperature difference across the evaporator to maintain the condition of maximum capacity (as shown in figure 8). This scheme will have little or no control signal. The temperature measurement used in the feedback loop also has significant Gaussian noise. These are some of the reasons why TXV systems often exhibit a "hunting" phenomenon. Hunting becomes more and more prevalent as the phase lag increases. The valve will oscillate from open to closed, unable to stabilize.

Figure 8 also suggests that COP is not significantly compromised at the point where capacity seems to reach its maximum.

CONCLUSION

A new sensor was presented that can sense refrigerant with low LMF. The dynamics of the sensor allow it to detect saturated liquid droplets in superheated vapor. The sensor is able to predict certain system parameters within the operation range of the sensor. A signal from the sensor can be used in a control scheme to maintain an air conditioning system at a desired system performance.

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