Internal Heat Exchanger Performance Quantification and Comparison Testing Methods Including Exploration of the Effects of Location of Measurements and Oil in Circulation

Andrew Musser
Creative Thermal Solutions, Inc., United States of America, musser@gmail.com

Pega Hrnjak
pega@creativethermalsolutions.com

Stefan Elbel
stefan.elbel@creativethermalsolutions.com

Internal Heat Exchanger Performance Quantification and Comparison Testing Methods Including Exploration of the Effects of Location of Measurements and Oil in Circulation

Andrew MUSSER[1]*, Pega HRNJAK[1], Stefan ELBEL[1]

[1]Creative Thermal Solutions, Inc.
Urbana, IL, USA
(217) 344-7663, andrew.musser@creativethermalsolutions.com

* Corresponding Author

ABSTRACT

The Internal Heat Exchanger (IHX) is well known for its potential to improve the performance of air conditioning systems. The adoption of alternative, more environmentally friendly, refrigerants such as R744 has brought elevated attention to IHX development due to relatively large performance increases from IHX usage compared to conventional refrigerants. Many alternative refrigerants exhibit performance shortfalls thus furthering the need for system enhancements such as IHX introduction. In addition, the increasing need for even small incremental improvements in systems using conventional refrigerants, and EPA credits for such improvements, has driven the expanded development and implementation of IHXs. The focus of this paper is the evaluation of test methods commonly used for quantification and comparison of the performance of internal heat exchangers and the effects of location of measurements and oil in circulation rates on the measurement accuracy and actual IHX performance. Typical IHX performance measurements yield the heat exchanger capacity, effectiveness, and the refrigerant pressure drop across each side of the heat exchanger. Existing test standards vary widely on the required test conditions, allowable oil in circulation rates, and instrumentation locations. The goal of comparison testing is, of course, to accurately quantify performance while also achieving repeatable results which allow for a fair and useful comparison between IHXs. Test conditions and temperature measurement location can have a large effect on both the accuracy and repeatability of measurements. Conditions close to the saturation dome, i.e. low subcooling or superheat, can make it difficult to accurately determine and control the state point while high superheat presents an unrealistic operating condition which can limit the impact of the IHX. Thermal stratification across the cross section of the IHX tubes can also lead to measurement inconsistency depending on the temperature probe placement. Oil in circulation rates directly factor into the heat exchanger capacity calculations but also can affect the actual heat exchanged. This paper will discuss these effects and their implications on standard development and test facility design.

1. INTRODUCTION

Internal heat exchanger usage is becoming increasingly commonplace in the automotive industry in order to increase the cooling capacity and COP of A/C systems. Capacity improvement is readily available however effects on the refrigeration cycle must be considered when determining potential impact on COP. For example the added enthalpy difference across the evaporator may be more than offset by compressor power consumption and drop in mass flow rate if IHX low side pressure drop is too high. In order to understand the impacts of the IHX, several performance metrics are calculated including heat exchanger capacity, heat exchanger effectiveness, and refrigerant pressure drop across the heat exchanger. In order to calculate these values, pressure and temperature must be measured at each inlet and outlet in addition to refrigerant mass flow rate and oil in circulation rate (OCR). The fashion in which the above measurements are recorded can have a significant impact on the results. This paper will focus on temperature and OCR measurements and the related effects on measured and actual IHX performance. Figure 1 shows the typical appearance of a coaxial IHX for automotive use.

Figure 1: Typical Coaxial IHX

2. BACKGROUND

The internal heat exchanger uses the cold refrigerant at the evaporator exit to push the evaporator inlet further to the left side of the cycle. Figure 2 shows the added capacity on the left side of the cycle with the consequence of added compressor power on the right side of the cycle. COP will increase when the ratio of added compressor power divided by the original compressor power is less than the ratio of added capacity divided the original capacity. The compressor inlet condition must be considered such that superheating and corresponding elevated suction temperatures caused by the IHX does not result in excessively high discharge temperatures at high load conditions. In addition, if the IHX pressure drop is high, the added compressor power and drop in suction density and mass flow rate may negate gains in evaporator enthalpy difference and cause capacity and/or COP to decrease.

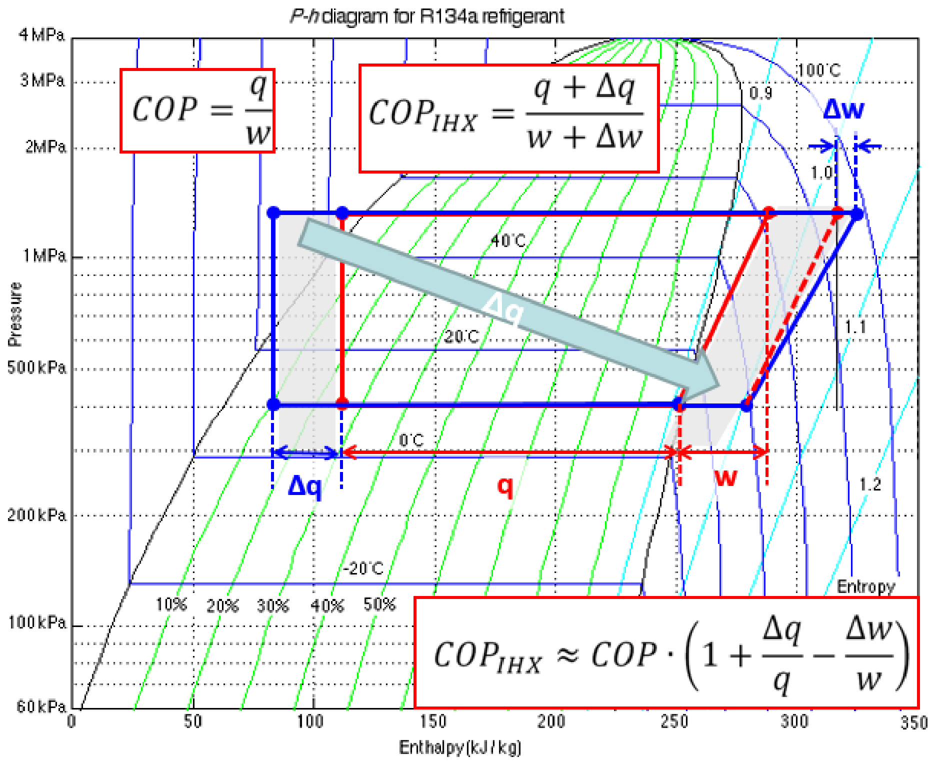

Figure 2: Cycle Improvement Attainable Using an IHX

3. EXPERIMENTAL FACILITY

The test facility used in the IHX study was designed based on the SAE Surface Vehicle Standard, J2765; Procedure for Measuring System COP [Coefficient of Performance] of a Mobile Air Conditioning System on a Test Bench (SAE, 2008). The facility consists of two environmental calorimeters. The outdoor environmental chamber produced the ambient conditions experienced by the front end vehicle components of the system including the condenser, internal heat exchanger, and compressor. The indoor chamber produced the conditions experienced by the evaporator. Each chamber contains a wind tunnel designed according to ASHRAE standard 41.2 (ASHRAE, 1987). In the case of both wind tunnels, the air passes through the heat exchangers, flow mixers, and then flow measuring nozzles. Thermocouples in the nozzle throat are then used in the airflow calculation as well as for the bulk air outlet temperature for each heat exchanger in the energy balance calculations. The setup was designed to replicate the actual relative heights of components in the vehicle. Three independent methods for calculating cooling capacity were used which exceeds the requirement of 2 independent methods in the SAE standard. The 3 methods used to determine capacity were the refrigerant side energy balance, air side energy balance, and a calorimeter energy balance where all energy entering and leaving the indoor calorimeter is measured with the balance being the capacity of the indoor heat exchanger.

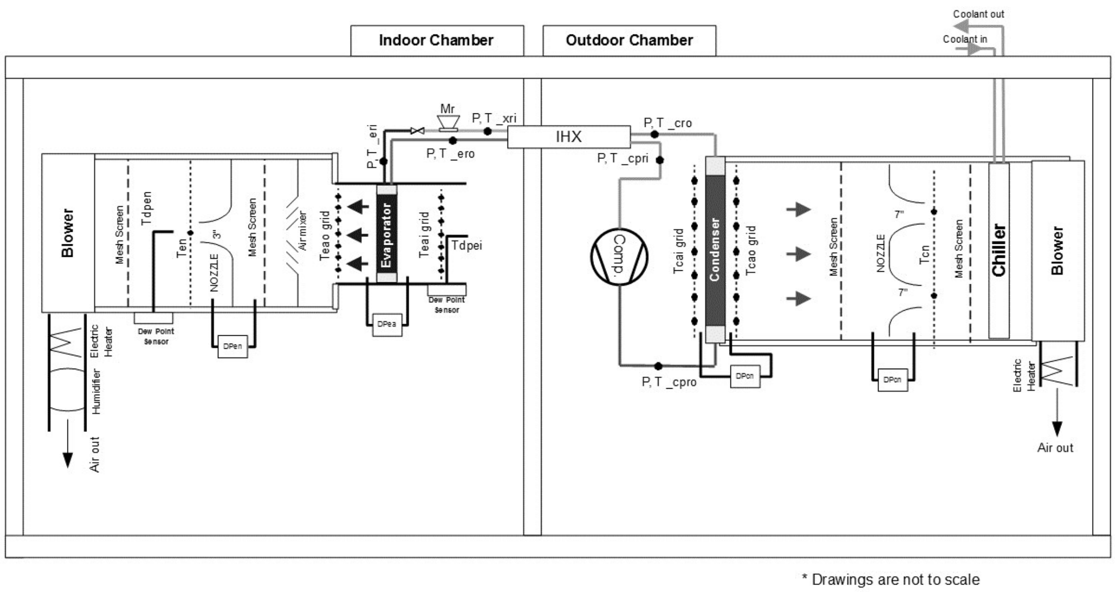

Figure 3: Experimental Facility

Testing internal heat exchangers in a complete system facility has several advantages. The first advantage involves testing the IHX in a production vehicle system exposed to real operating conditions and environments. The ambient conditions must then be adjusted to meet the IHX standard test conditions and offers a "reality check" if the conditions needed are extremely far from what would be a realistic operating condition for the vehicle. A second advantage is obtained by using the 3 independent energy balances available for evaporator capacity. The refrigerant based energy balance is heavily affected by the refrigerant mass flow rate, the OCR, the IHX low side inlet temperature and pressure (used to calculate evaporator exit enthalpy), and the IHX high side exit temperature and pressure (used to calculate evaporator inlet enthalpy). By verifying the refrigerant based capacity measurement against the air-side and chamber-side balances, nearly all measurements that go into the IHX performance metrics are covered. Furthermore, a similar balance between refrigerant-side and air-side measurements can be made for the condenser, thus verifying the measurements made for the IHX high-side inlet conditions (used to calculate condenser exit enthalpy). All of the above checks can greatly increase the confidence in the IHX related measurements. The cooling capacity measured on the air-side and/or chamber-side can also be used to back calculate the evaporator exit/IHX inlet state point in the case of a 2-phase evaporator exit condition which would be realistic for typical in-vehicle operation for IHX systems.

4. MEASURED DATA AND CALCULATIONS

IHX Efficiency (or Enthalpy Effectiveness) is one primary measure of the internal heat exchanger performance. IHX efficiency can be calculated using the following equation.

$$\eta IHX = \frac{H(at\ T_{IHX\ LP\ out}\ \&\ P_{IHX\ LP\ out}) - H(at\ T_{IHX\ LP\ in}\ \&\ P_{IHX\ LP\ in})}{H(at\ T_{IHX\ HP\ in}\ \&\ P_{IHX\ LP\ out}) - H(at\ T_{IHX\ LP\ in}\ \&\ P_{IHX\ LP\ in})} \quad (1)$$

$$H = Enthalpy, T = Temperature, P = Pressure, LP = Low\ Pressure, HP = High\ Pressure$$

IHX capacity can be calculated using both the low side and high side enthalpy differences multiplied by the OCR adjusted refrigerant mass flow rate.

$$Q_{IHX\ Low} = \dot{m_{ref}} * [H(at\ T_{IHX\ LP\ out}\ \&\ P_{IHX\ LP\ out}) - H(at\ T_{IHX\ LP\ in}\ \&\ P_{IHX\ LP\ in})] \quad (2)$$

$$Q_{IHX\ High} = \dot{m_{ref}} * [H(at\ T_{IHX\ HP\ in}\ \&\ P_{IHX\ HP\ in}) - H(at\ T_{IHX\ HP\ out}\ \&\ P_{IHX\ HP\ out})]$$

Accurate measurement of temperature is integral to the above calculations. Typically, IHX test standards specify an immersion style or surface mounted thermocouple located within 25mm of the IHX inlet or exit. This specification can cause inaccuracies of measurement particularly on the low side outlet where temperature stratification across the cross section of the tube can yield large differences in temperature measurement and thus capacity and IHX efficiency depending on the location of the thermocouple. Figure 4 shows the cross sectional view for an example coaxial style IHX (Tsuchiya, 2000). The larger interior suction line often exhibits thermal stratification across the cross-section of the tube.

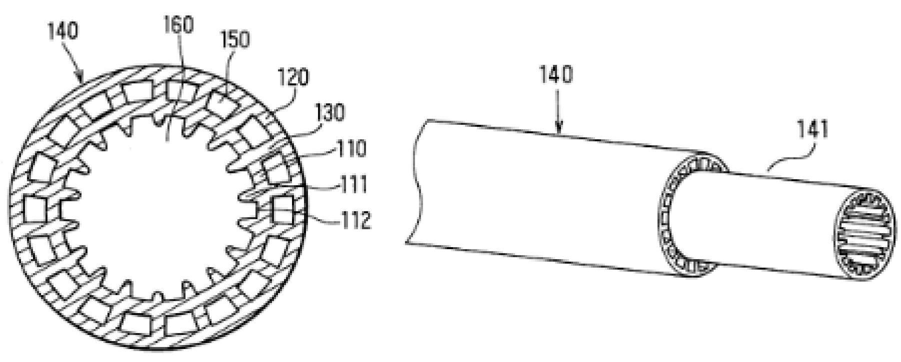

Figure 4: Example Cross Section for Coaxial IHX

Table 1 shows the effect of low side exit temperature probe location on the measured temperature. Condition A shows a 3°C temperature variance depending on the measurement location which is 15% of the 20°C total low side temperature change for this condition. Thus, the impact on the capacity and efficiency calculations can be very large depending on thermocouple probe location. Location 1 is an immersion probe in the location specified by most standards at 25mm from the low side exit. Locations 2, 3, and 4 are three equally spaced immersion probes covering the cross section of the IHX tube immediately downstream of Location 1. Location 5 is an immersion probe 200mm downstream of the low side exit after a static mixer was introduced. When comparing the energy balances, the temperature measurement after the static mixer at Location 5 yielded the best results, as expected, due to the well mixed uniform temperature profile achieved using the mixer. Figure 5 shows an example static mixer which can be inserted into the tubes directly after (or before) the IHX to unify the temperature profile (Schulz-Hanke, 2009). Static mixers, such as the one shown in Figure 5, are more commonly used to mix reactive components in joining applications but are ideal for laboratory purposes as well. If a static mixer is used, the pressure drop across the IHX must be measured directly at the IHX inlet and exit so as not to include pressure drop induced by the mixer.

Table 1: **IHX Low Side Exit Temperature at Multiple Locations**

	Location 1	Location 2	Location 3	Location 4	Location 5
Condition A	29.9°C	28.7°C	29.5°C	27.0°C	27.0°C
Condition B	24.5°C	24.7°C	24.6°C	23.9°C	23.0°C
Condition C	21.6°C	20.6°C	20.3°C	20.4°C	20.3°C

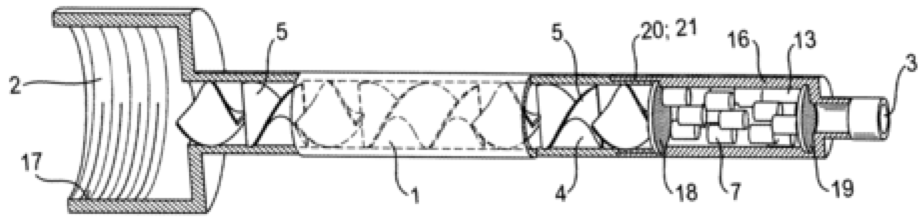

Figure 5: Static Mixer Example

5. OCR Effect on Measurement and Performance

Oil in circulation rate (OCR) requirements vary widely in various test standards. Some standards specify a maximum OCR while others give either very wide (1% to 5%) or very narrow (1% +/- 0.1%) ranges. Testing in a real system limits the ability to tightly control OCR, however, the impact of oil can have a significant effect on IHX capacity. Typically, oil is thought to degrade heat transfer by coating tube surfaces and reducing heat transfer coefficients however the opposite effect has been observed at very low oil in circulation rates for superheated IHX test conditions. Figure 6 shows an increase in normalized capacity as OCR increases from 0 to 1%. It is believed that wetting of the IHX surfaces due to the oil in circulation has a positive effect on heat transfer under the high superheat conditions on the low side of the IHX. In addition, foaming caused by the oil can increase heat transfer (Kim, 2012).

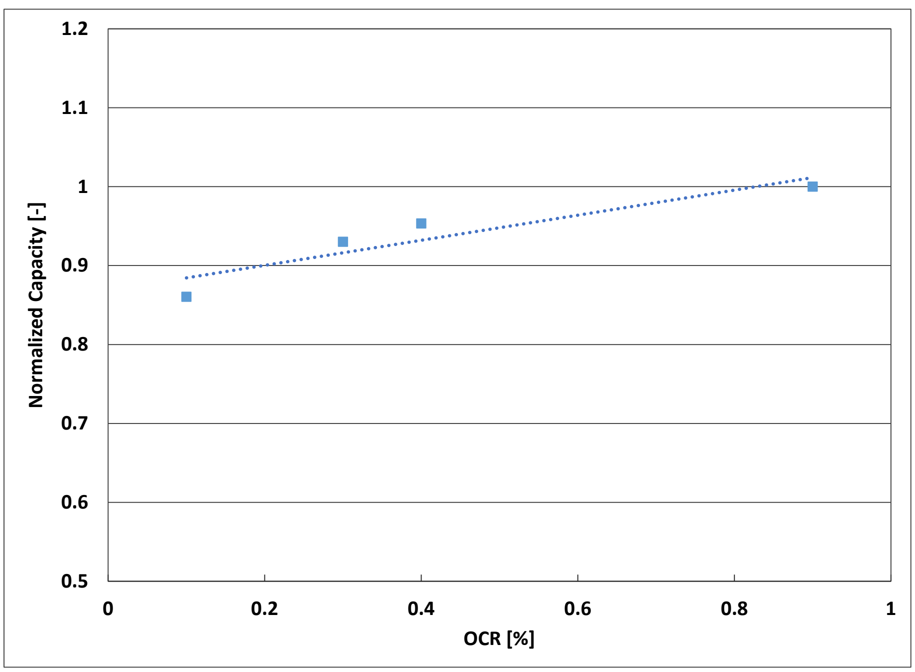

Figure 6: Effect of OCR on IHX Capacity

6. Conclusions

The Internal Heat Exchanger (IHX) offers significant potential to improve the performance of automotive air conditioning systems. The adoption of alternative, more environmentally friendly, refrigerants has brought elevated attention to IHX development due to relatively large performance increases and/or reduced overall performance which can be partially mitigated by the introduction of an IHX. Recent EPA credits have also led to IHX adoption as fleets work to meet carbon targets. This study elaborated on comparison of the performance of internal heat exchangers and the effects of location of measurements and oil in circulation rates on the measurement accuracy and actual IHX performance. Typical IHX performance measurements yield the heat exchanger capacity, effectiveness, and the refrigerant pressure drop across each side of the heat exchanger. Existing test standards vary widely on the required test conditions, allowable oil in circulation rates, and instrument locations. The goal of comparison testing is to accurately quantify performance while also achieving repeatable results which allow for a fair and useful comparison between IHXs. Test conditions and temperature measurement location can have a large effect on both the accuracy and repeatability of measurements. Temperature probe location was shown to affect IHX capacity by 15%. Static mixers were presented as an option to better mix refrigerant flow prior to temperature measurement. Conditions close to the saturation dome, i.e. low subcooling or superheat, can make it difficult to accurately determine and control the state point while high superheat presents an unrealistic operating condition which can limit the impact of the IHX. Testing in a full system was presented as an option to use other available energy balances to locate state points found at a potential two-phase evaporator exit. Oil in circulation rates directly factor into the heat exchanger capacity calculations but also can affect the actual heat exchanged as well as the measurements themselves. This paper showed that under low OCR conditions the IHX capacity counterintuitively increases as OCR increases.

REFERENCES

ASHRAE Standard 41.2, (1987). Standard Methods for Laboratory Airflow Measurement

Domanski, P.A., (1995). Theoretical Evaluation of the Vapor Compression Cycle with a Liquid-line/Suction-line Heat Exchanger, Economizer, and Ejector, National Institute of Standards and Technology, Report NISTIR 5606, Gaithersburg, MD, USA

Kim, S., and Hrnjak, P. S., (2012). "Effect of Oil on Flow Boiling Heat Transfer and Flow Patterns of CO2 in 11.2 mm Horizontal Smooth and Enhanced Tube." *International Refrigeration and Air Conditioning Conference at Purdue*. West Lafayette, IN, USA.

SAE Surface Vehicle Standard J2765 (2008). Procedure for Measuring System COP [Coefficient of Performance] of a Mobile Air Conditioning System on a Test Bench

Schulz-Hanke, W., Jakobstroeer, P., (2009). US Patent 7484881 B2, Washington, DC: U.S.A.

Tsuchiya, S., Isaji, A., (2000). US Patent 6098704 A, Washington, DC: U.S.A.