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Development of Efficient R-134a A/C System of a Medium Size Car

A.D. Desai*[1], S.N. Sapali[#], and G.V. Parthasarathi[&]

Abstract *– Automotive air conditioning (A/C) system is constantly undergoing improvements over the past decades to achieve higher efficiency. Internal heat exchanger (IHX) so far, has not been given much importance to use in car A/C systems. The IHX transfers heat from the condenser outlet to the suction gas. Although previous researchers have investigated performance of IHX, this study can be distinguished from the previous studies with respect to the type, size and material used for its construction. This paper describes the one possible way to improve cooling capacity, COP and energy efficiency of R-134a A/C system of a medium size car. Three different experiments/tests are conducted under steady state conditions in a system test bench calorimeter, one without heat exchanger (baseline) and other two with different heat exchangers. The experimental results show that cooling capacity of car A/C system increases by 4.84% and 3.17%, COP increases by 11% and 7.18% and compressor input power is reduced by 6.05% and 4.18% with the use of copper and aluminum IHX, respectively.*

Keywords – Calorimeter, car A/C system, cooling capacity, COP, internal heat exchanger (IHX), subcooling.

1. INTRODUCTION

Many technologies are being used for enhancing automotive R-134a A/C system performance. The IHX technology is probably the simple one, yet it has not being given importance for its use on production vehicles. The IHX transfers heat from the condenser outlet to the suction gas for waste refrigeration recovery. The increased subcooling before expansion reduces evaporator inlet enthalpy and thus increases the specific cooling capacity. The increased superheating of gas before compression reduces suction vapor density and increases compressor inlet temperature. The important strategy to be adopted while using IHX technology is to maximize subcooling and minimize superheating. The balance is to be maintained between subcooling and superheating in-order to achieve the efficient performance of A/C system.

Kim *et al.* [1] studied the effect of liquid line suction line heat exchanger (LLSL-HX) for residential heat pump with R-22, R-134a, R32/134a, R-407C and R-410 as a refrigerant. However, LLSL-HX is not used for car A/C system. Boewe *et al.* [2] used tube in tube type suction line heat exchanger with different tube lengths in transcritical R-744 mobile A/C system. All commercially available components are used but results are taken with different compressors with a maximum rpm of 1800. Bullard *et al.* [3] presented the results of experimental runs of a prototype of R-744 refrigeration system meant for a compact car. They used LLSL-HX but its effects are not discussed in their paper. Klein *et al.* [4] identified new dimensionless parameter attributable to LLSL-HX. They assumed the pressure drop in LLSL-HX to be negligible. Also the test conditions are not well defined. Brown and Domanski [5] used LLSL-HX in a semi-theoretical simulation model for a transcritical CO_2 mobile A/C System. Brown *et al.* [6] carried out comparative analysis of an automotive A/C system operating with CO_2 and R-134a, using IHX. The paper discussed only the simulation results. They did not consider separately the effect of IHX. Marcus *et al.* [7] performed experiments with Fixed Orifice Tube (FOT) and thermostatic expansion valve (TXV). It is concluded that FOT is more beneficial and IHX helped to improve the efficiency of R-134a A/C system. They do not mention the type of IHX used. Zang *et al.* [8] tested the LLSL-HX on a production vehicle with R-134a A/C system. They concluded that A/C systems with LLSL-HX have benefits viz. low compressor discharge pressure, better performance and there was no wet compression. Also the test conditions are not well defined. Kim *et al.* [9] experimental performance characteristics of zoetrope are compared with R-12, R-134a, R-22 and R-290 at high temperature heating and cooling conditions including those using liquid-line/suction-line heat exchanger. It is concluded that IHX increased the performance of heat pump, however it is not used for automotive A/C system. McEnaney *et al.* [10] presented experimental analysis of the performance of a prototype A/C system based on transcritical operation with R-744 as a refrigerant. IHX was included in A/C system but its effects are not discussed.

This paper presents the effect of IHX on cooling capacity, power consumption and coefficient of

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performance (COP) of medium size car A/C system. The wind tunnel results under various operating conditions of vehicle are used as a support or "real-world" data to design the IHX. Two tube-in tube type internal heat exchangers of unequal lengths but of different materials are designed, fabricated and are tested under steady state conditions on a system test bench calorimeter. Keeping same, all the A/C components and the connecting tubes, of actual R-134a A/C system of a medium size car, experiments are performed with two different IHX and one without IHX (base line), under steady state conditions. The IHX(s) are of tube in tube type heat exchanger, with fins on external surface of inner tube. The cold fluid (*i.e.* vapour refrigerant at outlet of evaporator-lower side) flows in the inner tube and hot fluid (*i.e.* liquid refrigerant at outlet from condenser-higher side) between the annulus of inner and outer tube. The design is very compact and weights are very low for both the IHXs. The sizes i.e. lengths and outer diameters are so selected that the IHX can be easily accommodated in the space available in car bonnet. Such a comparative study of car A/C system comprising of compact IHX made up of copper and aluminum material is not available in the open literature.

2. DESCRIPTION OF THE EXPERIMENTAL TEST BENCH CALORIMETER

2.1 Description

The schematic of test bench calorimeter, experimental test setup and Dew Point Unit (DPU) are shown in Figures 1, 2 and 3, respectively. The calorimeter and DPU helps to maintain the correct temperature and humidity of air as per given test conditions. These combined systems together can be used for testing complete HVAC modules as well as for testing bare components, viz. evaporator, condenser, compressor etc. of automotive A/C system, working with R-134a refrigerant. With this test bench, a "real life mounting" of a vehicle refrigerant circuit can be realized and hence it is utilized for testing complete automotive HVAC system under real vehicle conditions. The experimental test set up indicates various A/C system components, its tubings, location of IHX and sensors utilized during experimentation.

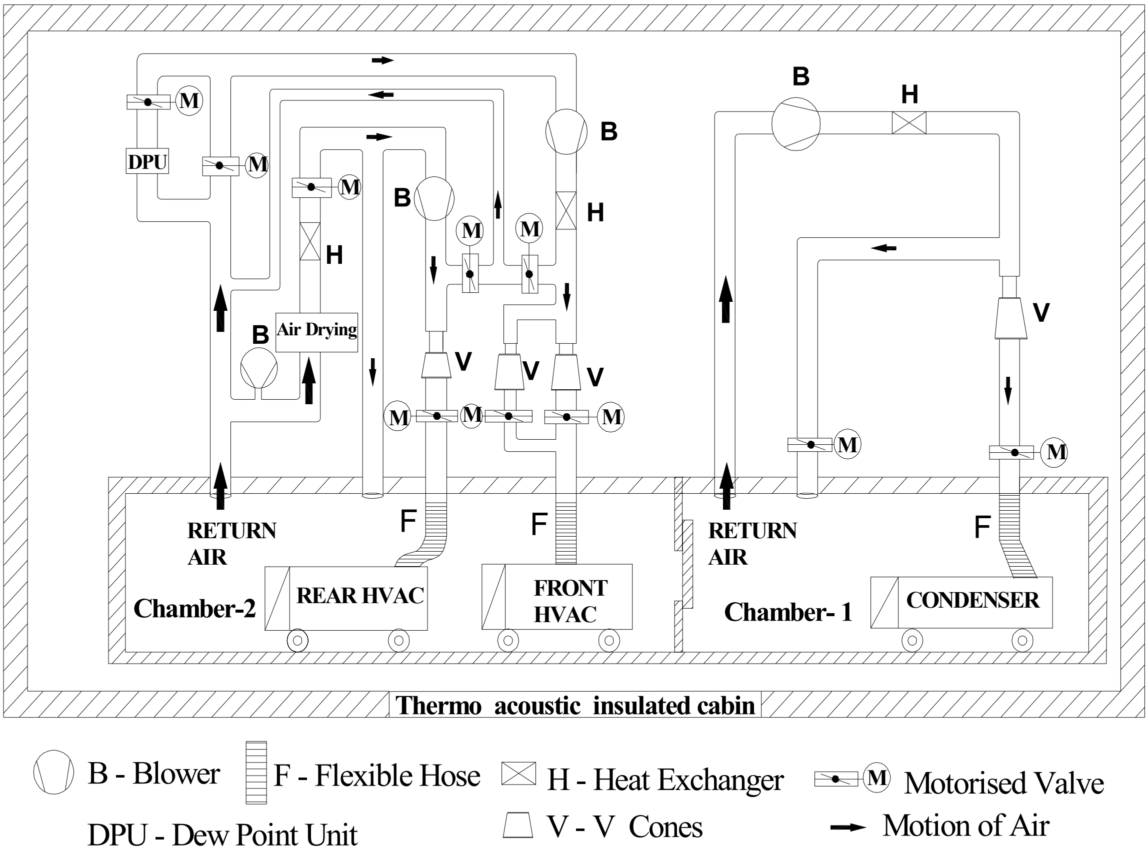

Fig. 1. Schematic of test bench calorimeter.

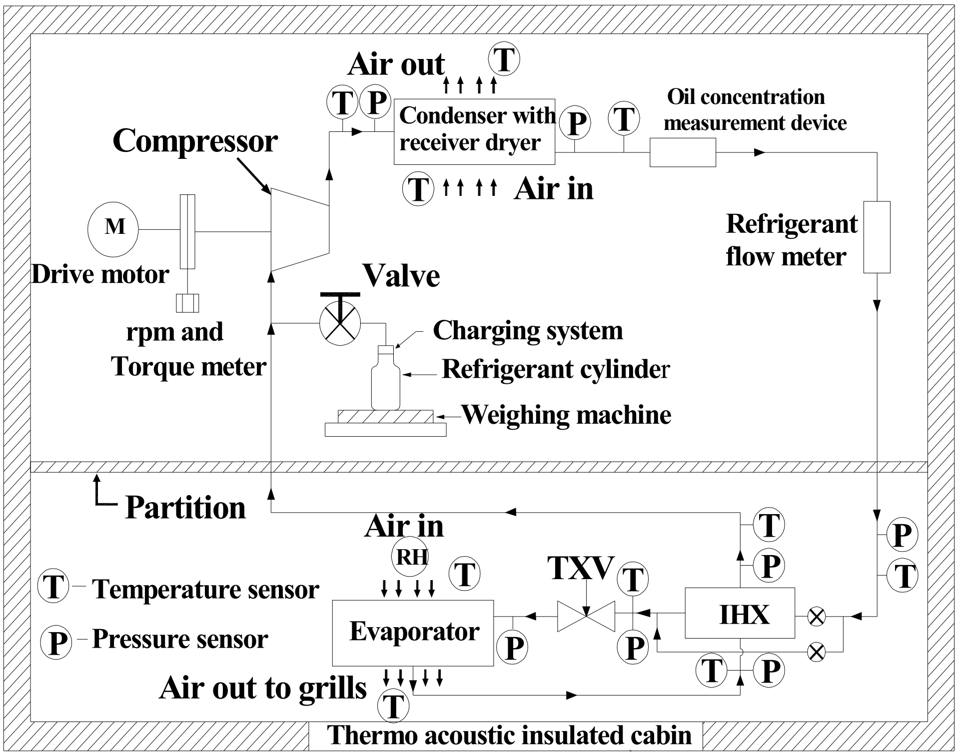

Fig. 2. Schematic of experimental test setup.

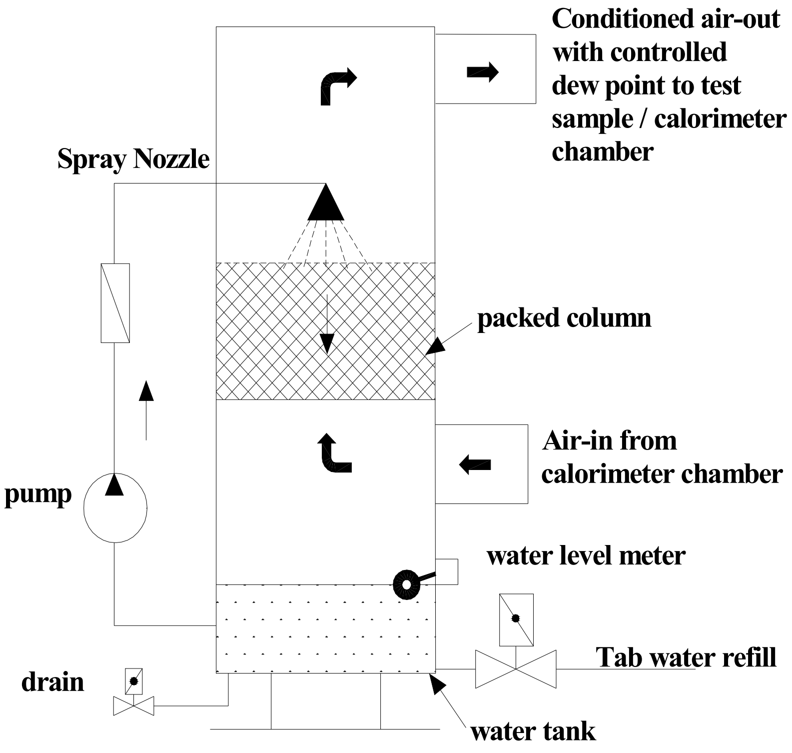

Fig. 3. Dew Point Unit (DPU) – for humidity control.

The entire test bench calorimeter consists of the following sub systems/modules.

1. Closed air loops for supply of conditioned air to condenser and evaporator.
2. R-134a refrigerant circuit with compressor drive, speed control device and torque meter.
3. Primary and secondary brine circuits of chiller units to achieve the desired temperatures of air.
4. DPU for controlling humidity of inlet air to condenser and evaporator.
5. V-cones for accurate measurement of air flow rates.
6. Lubricating oil concentration measuring device.
7. Coriolis type flow meter – for refrigerant mass flow measurement.
8. Power supply system for various drives (AC and DC both).
9. Control panel and data acquisition system.
10. Condensate measurement system - to determine latent heat load of moist air.

2.2 *Experimental Apparatus*

The double chamber layout is as shown in Figure 1. The chamber 1 is for testing condenser and compressor where as chamber 2 is meant for testing rear and front evaporators of automotive A/C system.

The components like radial blower with speed control unit, DPU, dehumidification unit, chiller, various sensors for measurement of pressures, temperatures, humidity, RPM, torque, mass flow rate of refrigerant and data acquisition system etc. are located inside the chambers. The airflow rate measuring V-cones, with gas tight flap are installed on top of the chambers. The complete system including air measuring sections are covered with noise and thermal insulation. The chamber / calorimeter is connected to the building ventilation system so that the heat load of the chamber / calorimeter can be dissipated to the atmosphere.

The water-cooled condenser of the cooling unit i.e. primary brine circuit is equipped with a flow control valve, which pumps the water into buffer tank from where the cold water is supplied to secondary circuit-heat exchangers. The heat exchangers in DPU and de-humidifier receive the water (hot/cold) from the secondary circuit, for controlling humidity in the test chamber.

The refrigerant leak detection and recharging system consisting a vacuum pump, nitrogen cylinder, refrigerant charging and recovery unit, along with lubricating unit and electronic weighing machine are separately available with necessary hoses and connections.

Figure 4 (a, b) and Figure 5 (a, b) show the inlet and outlet air temperature mappings of evaporator and condenser, respectively. Inlet air temperatures are measured by four numbers of PT-100 sensors and out let air temperatures by 16 numbers of K-type thermocouples in case of an evaporator and condenser, respectively. Four numbers and one number of humidity sensor(s) are used for measurement of humidity of inlet air at evaporator and condenser, respectively. The average of these values is considered for calculations. Thermocouples and pressure transducers are mounted at various locations as shown in Figure 2 for the measurement of refrigerant temperature and pressure. All the sensors used for the temperature, pressure, torque, RPM and humidity measurement are calibrated prior to their use.

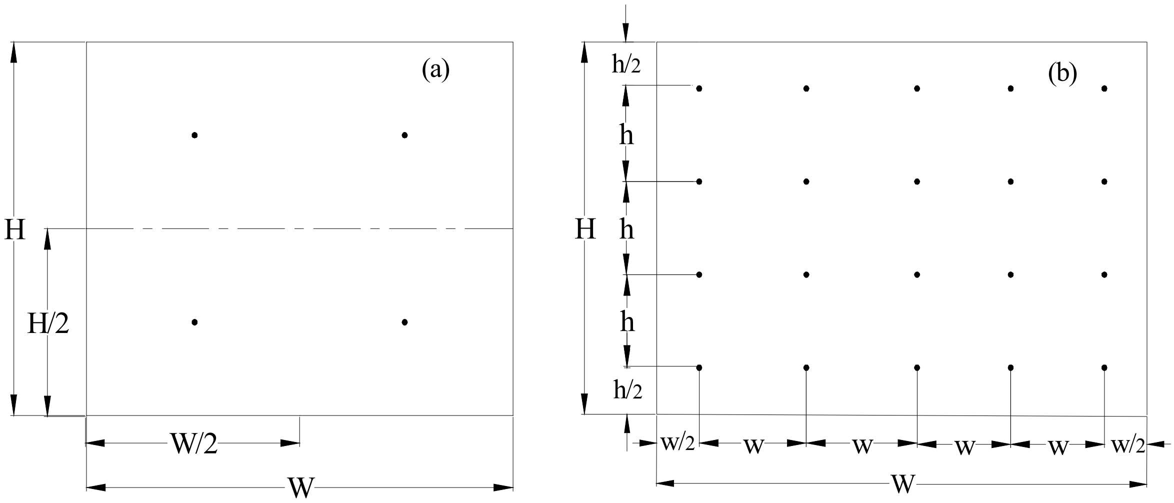

Fig. 4. (a) and (b) Evaporator inlet and outlet air temperature mappings.

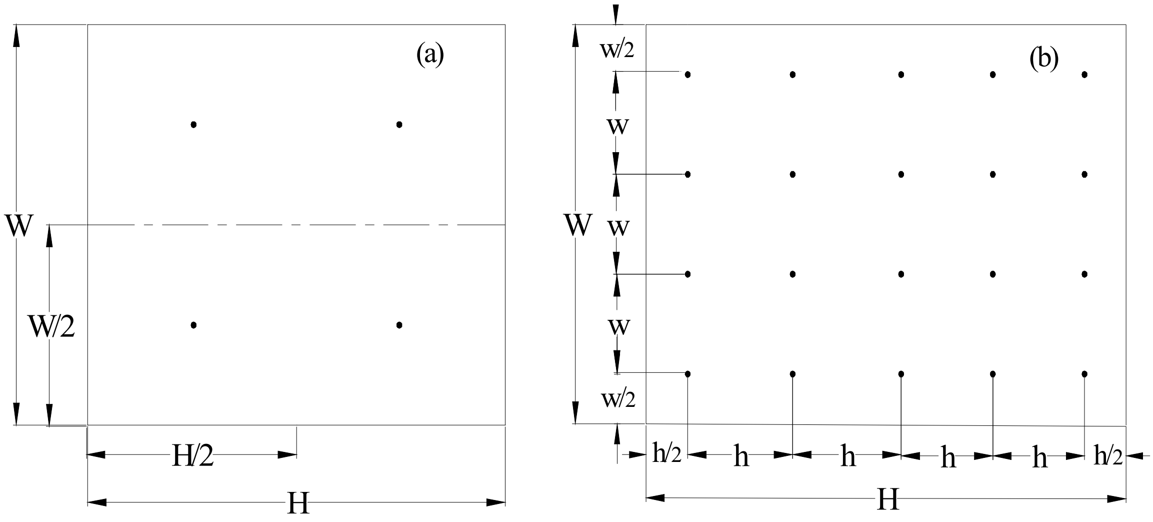

Fig. 5. (a) and (b) Condenser inlet and outlet air temperature mappings.

2.3 *Test conditions*

Manufacturers generally have their own test conditions rather than adopting an industry wide standard. This is done in order to be able to compare most recent test data with the historical data from previous testing. Table 1 shows the typical test conditions used during experiments and their significance. The airflow rates and the compressor rpm are selected, corresponding to blower knob position and vehicle speed, respectively. The various tests conditions are for dry, humid, moderate and high ambient conditions. The details of various test components utilized in these tests are given in Table 2.

Experimental procedure and measurements

All the actual components of A/C system of a medium size car are connected as shown in Figure 2.

The charge determination test as described below is conducted to determine optimum charge quantity required for effective operation of A/C system. This will ensure proper working of A/C system while driving at city and highway traffic conditions and varying ambient.

1. The A/C system is initially filled with nitrogen gas at a pressure of 5 to 5.5bar and this pressure is maintained for 30 minutes. Thus the system is assured for no leakages.
2. The A/C system is evacuated by nitrogen removal.
3. Through the refrigerant charging unit, to start with, feed the A/C system with a refrigerant charge of 350g. This charge quantity is approximately half of actual charge and it is selected based on past experience and historical data.
4. The system is allowed to stabilize for 10 minutes after each addition of charge between 25g - 50g, till desired values of subcooling and superheating are reached. In the present study superheating of refrigerant after evaporator between 5-12K and subcooling of refrigerant after condenser up to 10 K are considered for charge optimization.
5. Thus correct charge is determined as per above procedure for baseline and two IHX tests (copper and aluminum IHX) under consideration.
6. As per the tests conditions mentioned in Table 1 experiments are conducted. The operating parameters namely air flow rates, air temperatures at inlet to condenser and evaporator are varied through PID controller. The air flow rates over condenser are so selected to simulate the condition owing to actual vehicle speed. In the present study RH of air at evaporator inlet is also varied from dry ambient (RH< 10%) to humid ambient of 50% RH. The compressor rpm is varied from 600 rpm to a maximum value of 4000 rpm corresponding to idle and maximum speed (120 km/h) of a vehicle.
7. For each of the test condition the readings are recorded after the system gets stabilized. The pressures, temperatures, humidity and mass flow rates of air and refrigerant are recorded by data logging system at various locations as shown in Figures 1 and 2.
8. The mass flow rate of air over evaporator and condenser are measured using V-cones which are mounted on respective air inlet pipes.
9. Testing is done for humid, dry, moderate and high ambient conditions. The test conditions selected are severe as well as mild in nature corresponding to highway and city drive cycles.
10. The oil concentration in the refrigerant is also recorded during the test and it is found to be maximum of 5.02%, which is below the tolerable limit [17].The accuracies of measured parameters are given in Table 3.
11. The compressor input power is measured using the torque meter and its RPM.
12. Three tests/experiments are performed under steady state conditions one baseline (without IHX) and one each with copper and aluminum IHX. All the necessary observations and readings are recorded.

Table 1. Test conditions.

Test Condition No.	Condenser			Evaporator			Compressor	Significance of test
	Temperature of air at inlet	Air flow rate at inlet	Air flow Velocity	Air flow Rate at inlet	Temperature of air at inlet	RH of air at inlet	RPM	Blower knob position, vehicle speed, ambient conditions
	ºC	kg/min	m/s	kg/min	ºC	%	rev/min	
1.	38	34.92	2.9	9.0	38	50	2500	Within 5 minutes and cool down-stabilized
2.	43	18.96	1.6	9.0	43	<10 (dry)	1000	To check the hot gas temperature for different compressor RPM and at high load condition
3.	43	34.37	2.9	9.0	43	<10 (dry)	2500	
4.	43	45.04	3.8	9.0	43	<10 (dry)	4000	
5.	45	35.33	3.0	9.0	45	<10 (dry)	2000	4th speed, 60 km/h, high ambient.
6.	25	37.72	3	6.5	25	50	900	3rd speed, vehicle idle speed
7.	25	37.72	3	6.5	25	50	2500	3rd speed, 80 km/h, low and humid ambient.
8.	25	37.72	3.0	4.0	25	50	2000	2nd speed, 60 km/h, low and humid ambient.
9.	25	37.72	3.0	4.0	25	<20 (dry)	2000	2nd speed, 60 km/h, low ambient.
10.	35	18.24	1.5	6.5	25	<20 (dry)	1000	3rd speed, idle, low and dry ambient.
11.	35	18.24	1.5	4.0	25	<20 (dry)	600	2nd speed, vehicle idle, speed low and dry ambient.

***Note: These test condition are same for baseline (w/o IHX), copper and aluminum IHX tests.**

Table 2. Details of test components.

Sr.	Name of the Component	Description					
1.	Compressor SE BX-11 reciprocating type	Displacement 124.6 cc, Max RPM = 9000, Weight = 2.3 kg Lubricating oil grade and quantity ND8 – 140 cc compressor pulley diameter = 131 mm – 7 grove, pulley ratio=1.16, stroke length = 18.24 mm					
2.	Compressor clutch	Rating – 12 V, Engagement voltage – 8 V, Current – 3 to 3.4 A, Pulley Dia – 131 mm Pulley Type – PV 7, Static friction torque – 34 N-m					
		Width (mm)	Height (mm)	Depth (mm)	Flow path	Frontal area (m^2)	Mass (kg)
3.	Condenser (W* H * D) micro channel brazed aluminum 4 pass	312	567	16	14-10-4-3	0.1770	1.7
4.	Evaporator (W* H * D) micro channel brazed aluminum 4 pass	241	235	55	10-11- 10-11	0.0566	1.3
5.	TXV (Thermostatic Expansion valve)	C3 Charge and 1.9 bar setting					
6.	Internal Heat exchanger (IHX)	Co axial tube in tube type, Counter flow, with fins on external surface of inner tube.					
		Length (mm)	Outside Diameter (mm)	Mass (g)			
6.1	Material:- copper, externally finned inner tube	400	25	1150			
6.2	Material:- aluminium, externally finned inner tube	375	25	300			
7.	R-134a Charge quantity*	*Base line = 550 g *with copper IHX = 655 g *with aluminum IHX = 620 g					
8.		Connecting tube dimensions (mm)		Length of connecting tubes (mm)			
		Outer diameter	Thickness	copper IHX	aluminum IHX	Base line	
	Suction line	16	1.75	980	965	940	
	Liquid line	8	1	980	970	920	
	Discharge line	12	1	700	680	650	

***Note: All the A/C components of a vehicle are connected using actual piping and through calorimetric charge determination tests for base line, copper and aluminum IHX, the refrigerant optimum quantities are decided**.

Table 3. Accuracy of measured parameters.

Pressure	K type thermocouple	PT-100 sensor	Rotational Speed (RPM)	Humidity	Flow measurement	% of oil concentration	Weighing scale	Torque
High and Low ±1% (±2 Pa)	i) Air: ±1K ii) Refrigerant: ±0.1K	±0.5 K	±1%	±0.2 K of dew points in range 10^0C to 30^0C, For>30^0Cdew point ±0.5K	i) Air: ± 1% of measured value ii) Refrigerant: ±0.05% of full flow of measured value	± 0.01%	± 0.001g	± 0.2% of measured value

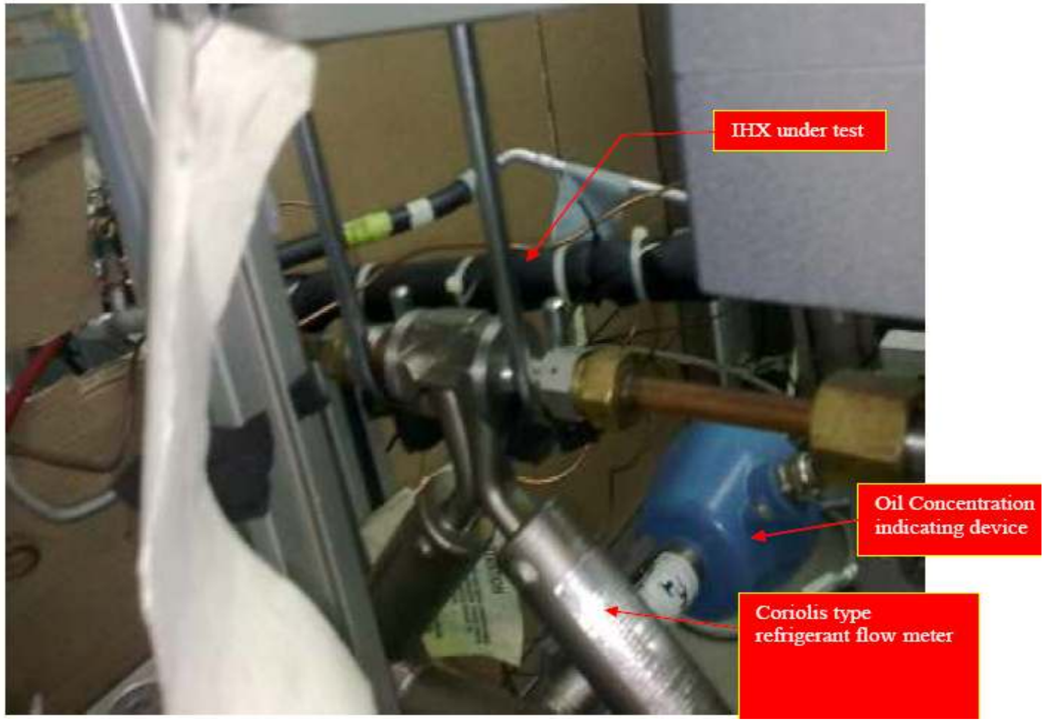

Fig. 6. Photo of location of IHX under test.

3. RESULTS AND DISCUSSION

The experimental data is processed so that the system performance can be evaluated for different operating / test conditions mentioned in Table 1, Figures 7, 8 and 9 shows the comparison of cooling capacity, COP and power input to compressor of AC system with and without IHX at various test conditions and compressor speeds. These graphs / figures are plotted by using the experimental data collected / recorded during these tests, for all the three tests viz. base line, with copper IHX and aluminum IHX. Minimum and maximum power consumption of compressor of A/C system of a medium size car is also determined corresponding to idle and maximum engine rpm. The results of these tests indicate significant influence of IHX on the performance of A/C system of a car. The minimum speed of compressor corresponds to idle condition and maximum speed to 120 km/h of actual vehicle speed.

Figure 7 shows the comparison of cooling capacity of the A/C system for above named three tests, with the variation of compressor speed, which is according to engine/vehicle speed variation. The cooling capacity of the A/C system is higher for the compressor speed of 2500 rpm with IHX made up of copper in comparison with base line system and the A/C system with aluminum IHX. The same trend is observed at all the other compressor speeds.

There is a better heat exchange rate, between the liquid refrigerant and vapor refrigerant in IHX due to high thermal conductivity of copper metal. This results in the reduction of superheat of suction gas and improves subcooling of liquid refrigerant before it enters into the expansion device. The average subcooling is found to be 12.23 K with copper IHX and 11.46 K with aluminum IHX and is within acceptable limits.

The cooling capacity of the system is minimum for the compressor speed of 600 rpm. The mass flow rate of refrigerant varies according to compressor speed, therefore, low speed leads to lower cooling capacity of the A/C system.

Figure 8 shows the comparison of COP of the A/C system for baseline and IHX tests, with the variation of compressor speed which in turn varies according to the engine /vehicle speed.

The COP is the ratio of cooling capacity to the input power of the compressor. This ratio is maximum at a compressor speed of 900 rpm, because of the fact that power consumption at low rpm is less. However the test conditions corresponding to compressor rpm of 600 are different than at 900 rpm. Hence the cooling effect and power consumptions are different at these compressor speeds resulting in to variation in COP.

Figure 9 shows the comparison of power input to the compressor of A/C system for baseline and IHX tests, with the variation of its speed which varies according to the engine speed. The input power to the compressor is a function of refrigerant flow and its speed. The mass flow rate of refrigerant is minimum corresponding to its minimum speed.

Further following points are observed.

1. The average refrigerant pressure drop in copper IHX is also very low of the order of 3.63 kPa on higher side and 2.45 kPa for low side. For aluminum IHX the pressure drop is 4.09 kPa and 1.36 kPa on higher side and low side, respectively.
2. The refrigerant superheating at compressor inlet is observed to be 12.17 K and 16.12 K for copper and aluminum IHX, respectively, which is also within tolerable limits and practice followed in industry.
3. There is significant influence of IHX on R-134a A/C system. It is observed that cooling capacity and COP increases and there is noticeable reduction in power input to the compressor.
4. The oil concentration in refrigerant, for base line, copper and aluminum IHX tests, is also measured and is observed to be 5.02%, 3.93% and 4.65%, respectively which is well within the prescribed value.

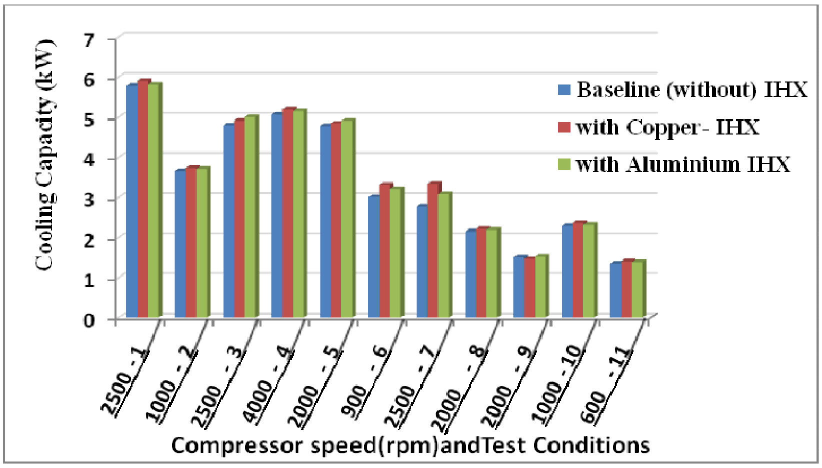

Fig. 7. Comparison of cooling capacity –baseline, with copper IHX and aluminium IHX.

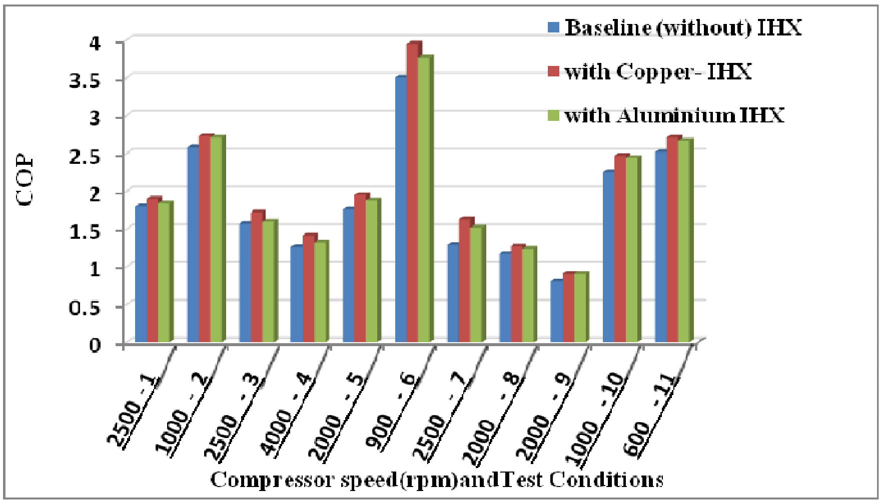

Fig. 8. Comparison of COP– baseline, with copper IHX and aluminium IHX.

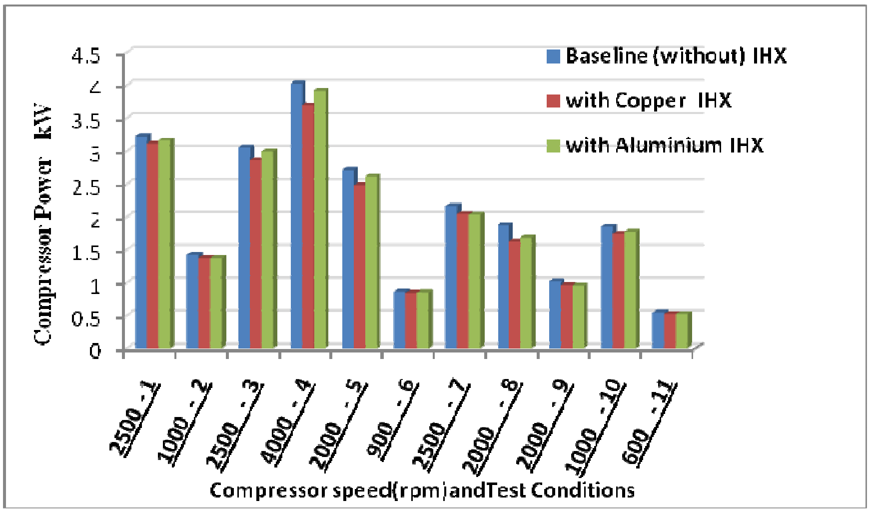

Fig. 9. Comparison of Power input to compressor- baseline, copper IHX and aluminium IHX.

4. CONCLUSION

The experiments performed on system test bench calorimeter and its results have proved that IHX improved the efficiency of R– 134a A/C system of a medium size car noticeably. The size and weight of IHX developed in this study is almost four times less as compared to the IHX sizes of previous studies.

1. The overall improvement in cooling capacity of A/C system with copper and aluminum IHX is 4.84% and 3.17%, respectively.
2. The COP has increased by 11% and 7.18% in case of copper and aluminum IHX, respectively.
3. The average compressor input power is reduced by 6.05% and 4.18% in case of copper and aluminum IHX, respectively.
4. The refrigerant pressure drop in IHX on higher side and lower side are very low as compared to the values.
5. The average refrigerant temperatures at compressor outlet are 74.34°C, 88.80°C and 91.09°C for base line, copper and aluminum IHX, respectively.
6. Minimum power consumption by compressor at 600 rpm corresponding to a vehicle/engine idle condition is found to be 0.54 kW for baseline, 0.52 kW each for copper and aluminum IHX. Similarly maximum power consumption by compressor at 4000 rpm corresponding to a vehicle speed of 120 km/h is found to be 4.02 kW for baseline, 3.69 kW for copper and 3.91 kW for aluminum IHX.

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