An Experimental Study on the Cooling Performance of Refrigerant (R134a/R1234yf) in Automobile HVAC System

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Abstract: The present work deals with the experimental investigation on the performance evaluation of R134a and R1234yf as automotive HVAC refrigerants. As the usage of R134a increases environmental issues due to its higher global warming potential (GWP), it is necessary to find an alternative without compromising the performance of the HVAC system. R1234yf having low GWP is one such drop-in alternative. But the COP of the system using R1234yf is observed to be low. Hence this work investigates on the effects of using an internal heat exchanger (IHX) with the conventional automotive HVAC system in the performance enhancement. The results indicate acceptable range of cooling capacity, COP and compressor discharge temperature for R1234yf when integrated with IHX and a high efficiency evaporator. COP of the R1234yf IHX system is observed to higher than the COP of R134a baseline system. The results of cooling capacity and compression discharge temperature of R1234yf IHX system also shows an enhancement and matches with the corresponding values of R134a baseline system.

Keywords: High efficiency evaporator; HVAC systems; Automobile HVAC; Internal Heat Exchanger; R134a; R1234yf

1. INTRODUCTION

Heating, Ventilation and Air Conditioning (HVAC) systems are an integral part of mechanical or automotive systems which are meant to achieve an environment which provides thermal comfort for processes and occupants along with better air quality. The primary components of an HVAC system as the name suggests are heating components, components for ventilation and cooling or air-conditioning components [1]. There is an escalation on luxurious and more comfortable travel needs or demands across the globe. Main aspect of this is the rising demand for air conditioning in automobiles. The main challenge faced by automotive HVAC is its high maintenance cost along with the government regulations for low emission solutions. Hence it is the need of hour to come up with automobile HVAC systems of low cost and small size which are equipped with automatic climate control features to meet the rising demand and environmental issues caused by conventional HVAC systems [2]. Due to these environmental issues, refrigerants like R1234yf which has a low global warming potential (GWP) of 4 are capturing attention over refrigerants like R134a which has a very high GWP of about1430. The thermodynamic properties of these two refrigerants are similar to each other, making R1234yf a significant alternative for R134a [3]. Many researchers confirmed this by conducting numerical and experimental investigations and one such work consider R1234yf as a drop in alternative of R134a because of its very low global warming potential and its usability in existing automobile air conditioning or HVAC systems with minimum modification in the system even though its coefficient of performance (COP) is low when compared to R134a [4].

The main concern of choosing new refrigerants over conventional ones is zero ozone depletion potential (ODP) and low global warming potential, but there are other challenges to deal with which includes cost, efficiency, operation and maintenance. According to experimental reports, R1234yf requires higher compressor work than R134a with a shorter run-time to complete the compressor cycle when compared to other refrigerants [5]. The ‘drop-in’ tests carried out for R1234yf and R134a by Lee et al considering summer and winter conditions of automotive air conditioners in a heat pump bench tester equipped with an open type compressor demonstrated satisfactory results with acceptable performance of R1234yf over R134a making it a dependable eco-friendly solution [6].

The effect of the presence of R1234yf in the energy and exergy of an automotive air conditioning system were experimentally investigated by Shin et al by varying compressor rotating speed and outdoor air temperature. The COP and total exergy destruction rate of the air-conditioning system using R134a-R1234yf mixture as refrigerant is low when compared to that of the system using R134a for an increase in outdoor air temperature, but the exergy efficiency was higher than that of the R134a system. Similarly, the cooling capacity and the exergy efficiency of the air conditioning system using the refrigerant mixture increased compared to that of the R134a system while the COP decreased with an increase in the compressor rotating speed. So, the presence of R1234yf in the R134a-R1234yf mixture decreases the total exergy destruction rate of the automobile refrigeration system and increases the exergy efficiency [7]. In an experiment done by Zilio et al., an automotive air conditioning system with baseline components which uses conventional R134a has been replaced with a drop-in R1234yf and the experimental results indicate low COP of R1234yf systems than the R134a system. But enhancement of the performance of R1234yf system is reported to be possible with some minor hardware modifications which include tuning of the thermal expansion valve setting for R1234yf, optimizing the control valve of variable displacement compressor and optimizing the condenser and evaporator refrigerant circuitries. The numerical investigation done on finding ways to enhance the COP of the R1234yf system for equal cooling capacities suggests an increase of the condenser and evaporator face area by 20% and 10% respectively along with the usage of overridden compressor to achieve higher COP values than the R134a baseline system [8].

In another work done by Cho et al., the performance evaluation of R1234yf was carried out by installing an internal heat exchanger (IHX) in order to improve the performance of the system. The results showed an improvement in performance by decreasing the difference between the cooling capacity (from 7 to 1.8%) and COP (from 4.5 to 2.9%) of R134a and R1234yf [9]. Joaquin et al. in his work compared R1234yf as a drop in alternative for R134a in a vapour compression system (VCS) under different working conditions by varying the compressor speed, the super heat temperature, the evaporating temperature and the condensing temperature. The cooling capacity and COP achieved with R1234yf in the baseline setup (R134a VC System) is low when compared with R134a. Even though low COP when compared to R134a, the R1234yf showed slightly better results for higher condensing temperatures and also the use of an internal heat exchanger (IHX) reduced the difference in the COP and cooling capacity values of R134a and R1234yf [10]. Air-cooled tube-fin heat exchangers are usually used as a condenser in the conventional automotive HVAC systems. Use of a liquid cooled heat exchanger as a condenser will be beneficial considering the size of the system [11].

The development in automobile industries with respect to electric vehicles (EVs) such as hybrid electric vehicles (HEVs), fuel cell electric vehicles (FCEVs), and battery electric vehicles (BEVs) has increased the challenges and need of new researches in the field of automotive HVAC systems from the viewpoint of enhancing fuel economy [12] [13]. The rapid development in new energy vehicles paves way for the requirement of novel HVAC system with environmental friendly refrigerants and which consumes less energy, as clean means of transportation is the emerging necessity. Refrigerants like R1234yf are suitable for electric vehicles. The direct expansion air conditioning system in EV's uses R1234yf as the refrigerant [14]

2. RESEARCH METHODOLOGY

The present work experimentally compares the performances of R134a and R1234yf in a baseline setup and then investigates on the performance enhancement by modifying the setup with a internal heat exchanger and fin-tube high efficiency evaporator.

2.1 Baseline Setup

A basic vapour compression system which serves as the working principle of most of the refrigeration and air conditioning systems comprises four main components which include a compressor, a condenser, an evaporator and a thermal expansion valve. Here the baseline system which is used as a standard for comparison is an R134a HVAC system, in which the R134a gets replaced with R1234yf and the performance evaluation is done.

Compressor is one of the main components in any heating ventilation and air-conditioning system (HVAC) in which the pressure and the temperature of gas are increased and the superheated vapour produced is pumped into the condenser. It sustains the flow of a refrigerant and thus is vital in a HVAC system. An 80CC vane rotary compressor has been used here for the experiment. Condenser in HVAC system helps in converting the superheated vapour into liquid state (Phase change) by reducing its temperature and this liquid is the saturated liquid which is later transferred into an evaporator. In an automotive HVAC, condenser is placed between the engine-cooling radiator and the car's grille where the refrigerant heat sheds and turns to refrigerant liquid which get transferred to the evaporator. An super high power (SPH) condenser of 16mm is taken for the experiment. Thermal Expansion Valve (TXV) reduces the pressure and temperature of the refrigerant coming from a condenser and gives a low-pressure refrigerant with less temperature to enter inside the evaporator. It actually controls rate of flow of refrigerant into the evaporator. Various cross-charged 2.0T TXV (Fujikoki) is used for the purpose. In automotive HVACs, evaporator is placed in the dashboard where the liquid refrigerant flows and then evaporates into cold vapour. This cold vapour or air cools the vehicle cabin. Evaporator releases cold air even if there is a leak in evaporator. It does not act as a heater core which leaks engine coolant into footwalls when damaged. The low-pressure liquid refrigerant is entered via the evaporator core and it is converted into cold vapour which cools and sometimes dehumidifies the air. In the baseline setup, a 38mm plate fin evaporator has been used.

The Table 1 shown below demonstrates the process parameters and combinations used for the performance evaluation which is generally followed in automobile industry. Compressor rotating speed (2500 RPM, 1800 RPM and 800 RPM) is tested for three different values of condenser inlet temperature (45°C, 37°C and 27 °C) and evaporator inlet temperature (43°C, 35°C and 25 °C).

Table 1: Evaluation Matrix

S.No	Compressor	Condenser Air Flow		Evaporator Air Flow		
	RPM	Flow (L/s)	Temp (°C)	Flow (L/s)	Temp (°C)	RH (%)
1	2500	700	45	140	43	40
2	1800	650	45	140	43	40
3	800	600	45	140	43	40
4	2500	700	37	140	35	40
5	1800	650	37	140	35	40
6	800	600	37	140	35	40
7	2500	700	27	100	25	40
8	1800	650	27	100	25	40
9	800	600	27	100	25	40

2.2 Modified Setup for Performance Enhancement

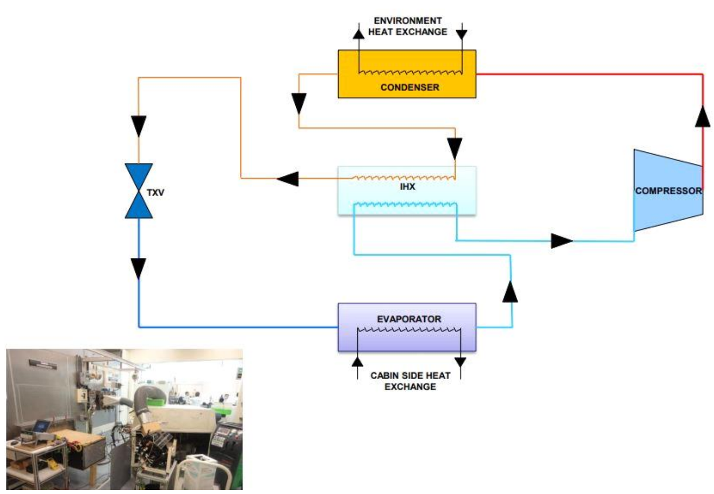

Figure 1: HVAC system with IHX

The modified setup is integrated with an internal heat exchanger and a high efficiency evaporator. An Internal Heat exchanger (IHX) is a device used to enhance the performance of HVAC system by subcooling the refrigerant before entering into evaporator. The main aim of internal heat exchanger is to transfer the heat between the zones of low and high pressure. This device is mainly introduced in an HVAC system to increase the heat transfer between the high temperature liquid entering into evaporator from condenser and the low temperature vapour entering into compressor from evaporator. This heat exchange helps in improving the cooling capacity and COP of the system by lowering the required inlet quality to evaporator. Thus, the air-conditioning and refrigeration manufactures highly use the internal heat exchangers as it helps in performing the refrigeration cycle more efficiently with any potential substitution of commonly used refrigerants like R134a. In order to recover the fuel economy, the efficient use of energy is necessary without compromising the vehicle performance. A substantial amount of energy is utilised by the HVAC systems which affect the fuel efficiency of vehicles which can be slightly overcome by incorporating an internal heat exchanger. But the presence of internal heat exchanger before a compressor possibly releases a higher temperature refrigerant into the compressor and thus causes adverse effects on the durability of the compressor. Thus, the application of internal heat exchanger in an HVAC system shall be considered.

The effect of IHX on automotive HVAC system using R1234yf is studied by many researchers recently and one of such work done by Direk et al. explains its significance with the results, where the cooling capacity observed to be increasing about 12% and COP showed an enhancement of about 6%. The power of compressor showed an improvement up to 8%. Volumetric and Isentropic efficiency also observed to be improved by reducing the total exergy destruction. So the usage of IHX with R1234yf in an automotive HVAC system will significantly improve the COP and cooling capacity [15]. Conventional automotive HVAC system usually consumes a significant amount of energy which effects fuel efficiency. The integration of IHX with the HVAC system reduces the energy consumption and thus improves the fuel efficiency. According to the experimental works done by Li et al, a decrease of 14% in energy consumption can be achieved at an environment temperature of 25°C [16]

The plate fin type evaporator of the baseline setup is replaced with a tube-fin type ensuring lower air side pressure drop. The evaporator made of prime-surface bare-tube coil is finned-tube evaporators. It contains the metals fins or plates to improve the surface area for transferring heat and is smaller in dimension but gives the similar heat transfer capacity like a larger prime-surface evaporator.

3. RESULTS AND DISCUSSIONS

3.1 Performance comparison of R134a and R1234yf

As seen from the figure 2, the P-T curve for both the refrigerants is observed similar. The saturation pressure of R1234yf is observed to be higher below 30°C and observed to be lower above 30°C when compared to R134a.

The Table 2 summarises the Superheat (SH) comparison between both the refrigerants at different evaporator inlet temperatures (25°C, 35°C, 43°C) for different compressor rotating speed (2500,1800 and 800 RPM).

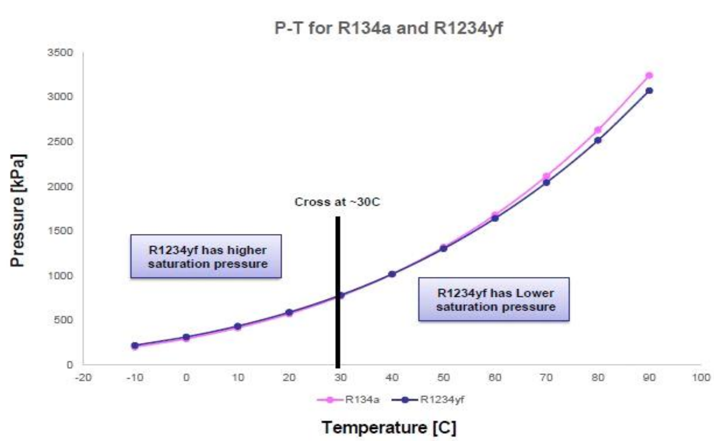

Figure 2: Pressure-Temperature Diagram for R134a and R1234yf.

Table 2: R134a and R1234yf SH

Evaporator Inlet Temp	Compressor Speed	R134a Baseline	R1234yf 2T high SH	R1234yf 2T low SH	R1234yf 2.5T high SH	R1234yf 2.5T low SH	R1234yf 1.75T high SH	R1234yf 1.75T low SH
°C	RPM	°C	°C	°C	°C	°C	°C	°C
25	800	1.5	7	1.5	5	1.3	5.8	1.7
25	1800	1.8	6.8	1.1	5	1.5	5.8	1.9
25	2500	1.6	6.5	0.9	5	0.8	5.8	2.1
35	800	6.2	10.3	6.2	8.7	6.4	12	8.2
35	1800	4.2	10	6.3	8.4	6.2	12.2	8.5
35	2500	3.9	10	0	8	6.4	10	9.7
43	800	10.2	13.2	10.2	13.9	10.2	14.5	12.3
43	1800	10.2	13.2	10.2	13.9	10.2	14.5	12.3
43	2500	6.4	14.1	10	12.3	8.6	16.1	14

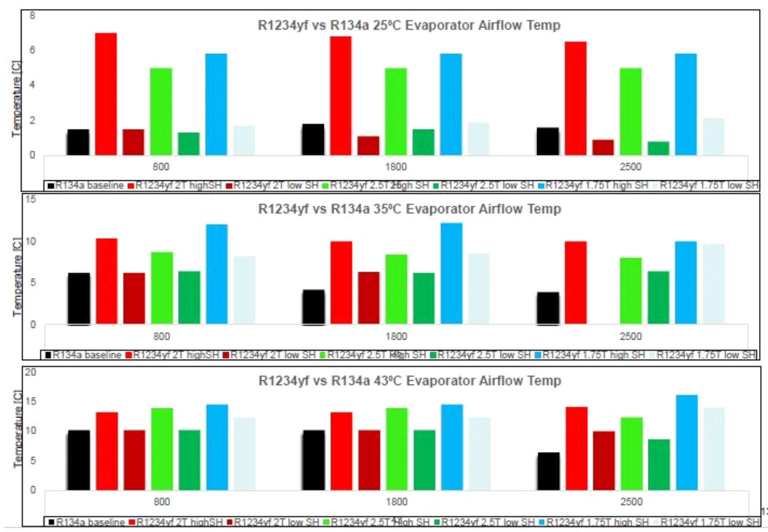

Figure 3: R134a and R1234yf SH Comparison

3.2 Effect of IHX on Cooling Capacity, COP and Compressor Discharge Temperature

As shown in Figure 4, the presence of IHX improves the cooling capacity of the HVAC system for both the refrigerants. The cooling capacity of R134a is observed to higher with and without (baseline) IHX when compared to R1234yf. But the capacity of R1234yf with IHX is in an acceptable range and closer to the values of R134a. The compressor rotating speed when varied from 800 to 1800 RPM showed an improvement in cooling capacity which later showed an adverse effect when changed to 2500RPM especially for R134a with IHX. The positive effect of IHX on the cooling capacity is observed to be hindered by the increasing compressor speed as the

R134a baseline has higher COP than R134a IHX when the compressor speed is at 1800 and 2500 RPM which is not the case for R1234yf where the IHX enhanced the cooling capacity more when the compressor speed is increased. Also the cooling capacity values are observed to be increasing with increase in evaporator inlet temperature as summarised in Table 3.

Table 3: Cooling Capacity

Evaporator Inlet Temp	Compressor Speed	R134a Baseline	R134a IHX	R1234yf Baseline	R1234yf IHX
°C	RPM	kW	kW	kW	kW
25	800	3.1	3.3	3	3.01
	1800	3.6	3.56	3.02	3.3
	2500	3.4	3.3	3.01	3.2
35	800	4.3	4.5	4.1	4.2
	1800	5.8	6.1	5.8	6.2
	2500	6	6.3	6	6.3
43	800	4.85	5.3	4.6	4.8
	1800	6.6	6.9	6.4	6.7
	2500	7.05	7.3	6.75	7.25

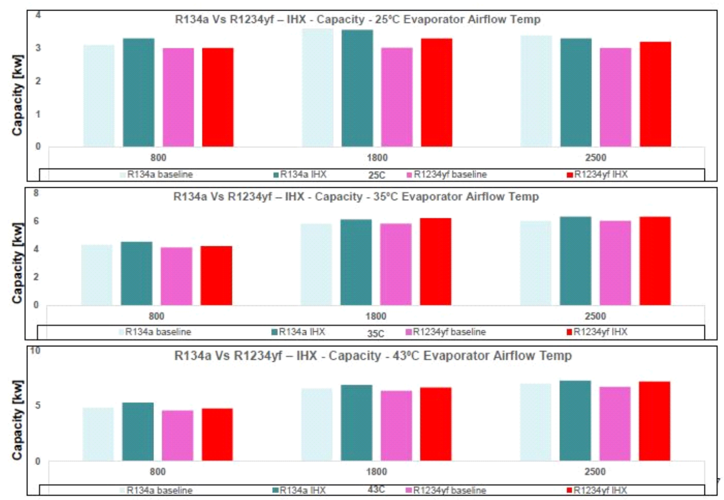

Figure 4: Cooling Capacity

Table 4: Cooling Capacity with IHX

Evaporator Inlet Temp	Compressor Speed	R134a Baseline	R134a IHX	R1234yf Baseline	R1234yf IHX
°C	RPM	COP	COP	COP	COP
25	800	4.2	4.25	4.2	4.33
	1800	3.5	3.58	3.58	3.5
	2500	3.05	3.25	3	3.3
35	800	3.8	4.19	3.72	4.05
	1800	2.3	2.5	2.38	2.49
	2500	2.01	2.35	2	2.28
43	800	3.21	3.25	3.2	3.2
	1800	2.38	2.4	2.3	2.41
	2500	1.35	1.45	1.25	1.35

The COP of the R1234yf with IHX is observed to be higher in most of the cases which explains clearly the significance of using an internal heat exchanger (IHX). The COP enhancement is visible for both the refrigerants and is prominent for R1234yf. COP observed to be decreasing with the increase of evaporator inlet temperature and compressor speed for all the system as demonstrated in Table 4 and Figure 5. The highest COP is observed for R1234yf with IHX at 25°C of evaporator inlet temperature for a compressor speed of 800RPM. The compressor discharge temperature also has a positive impact with the integration of IHX in the HVAC system. The highest values are observed to be for

R134a IHX system when compared to R1234yf IHX system but the values of R1234yf IHX system is still in acceptable range and more than the compressor discharge temperature of R134a baseline system.

Figure 5: Coefficient of Performance

So with the incorporation of IHX and a high efficiency evaporator, it is able to improve the performance of R1234yf in HVAC systems. The R1234yf IHX system as observed from the results showed better results when compared to R134a baseline system in the case of cooling capacity, COP and compressor discharge temperature.

Table 5: Compressor Discharge Temperature

Evaporator Inlet Temp	Compressor Speed	R134a Baseline	R134a IHX	R1234yf Baseline	R1234yf IHX
°C	RPM	°C	°C	°C	°C
25	800	48.5	60	46	51.5
	1800	48.5	60	46	52.5
	2500	50	61.8	47.8	53.4
35	800	62	73	60	65
	1800	79	90.1	70	80
	2500	80.25	91.5	72.8	80.25
43	800	74	84	70.5	78.5
	1800	90	103.5	83	91.8
	2500	90.8	112	90	100.05

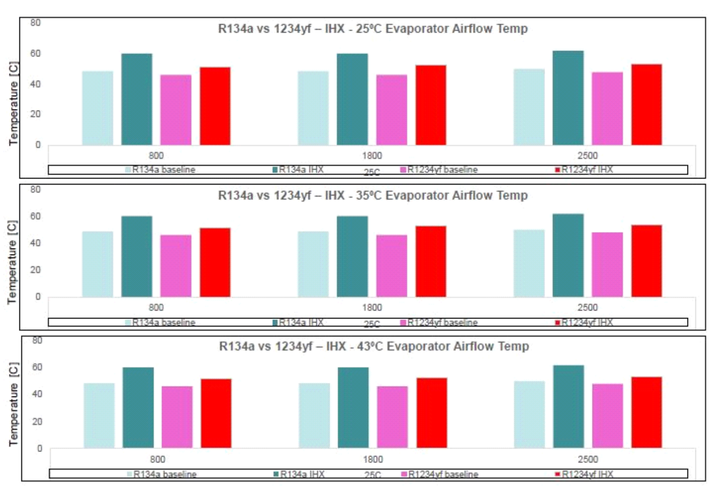

Figure 6: Compressor Discharge Temperature

4. CONCLUSIONS

The experimental investigation on the performances of R134a and R1234yf as refrigerants for automotive HVAC is done and the major findings are:

- The performance of R134a in terms of COP and cooling capacity is higher when compared to the drop-in R1234yf in the baseline setup.

- The integration of internal heat exchanger (IHX) and a high efficiency evaporator (tube-fin) with the baseline setup improved the performance of both the refrigerants, but R1234yf observed to be more beneficial with the presence of IHX and the modified evaporator of lower air side pressure drop.

- The COP, cooling capacity and the compressor discharge temperature is slightly more for R1234yf IHX incorporated HVAC system when compared to R134a baseline systems.

- Considering similar thermo-physical properties, better environmental impact due to low global warming and ozone depletion potential and acceptable and satisfactory performance with minor modification in the setup, R1234yf is a suitable and better alternative than R134a as an automotive HVAC refrigerant.

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