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Numerical and Performance Analysis of R290 Heat Pump Driven Air Conditioning System for Heating and Cooling

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Abstract

The demand for heating and air conditioning is rising due to rapidly changing climatic conditions. The market for heat pumps and air conditioning systems is seeing a steady increase in low global warming potential. There is a growing need to use environment-friendly refrigerants. Contemporary Refrigerants (HCFCs) such as those found in heat pump air conditioning systems have the potential to cause global warming and ozone depletion. Using more environmentally friendly refrigerants, including hydrocarbon and blend refrigerant mixtures, is one way to lower Global Warming Potential (GWP) and Ozone depletion potential. This study examines the performance of several alternative refrigerants, including R32, R134A, R410A, R22 and R290. To examine the performance of R290, theoretical and simulation results are compared for various refrigerants while taking into account several performance parameters, including the refrigerant energy efficiency ratio, mass flow rate, coefficient of performance, cooling capacity and compressor work for One Ton of Refrigeration (1TR) air conditioners. One player with a very low GWP is R290. However, the only drawback is that it can catch fire and is hazardous to use in split-type commercial heat pump air conditioning applications. The environmental and thermo physical properties of R290 are significantly better than those of other materials, according to theoretical and simulation studies utilising Cool Pack software, hence it is a viable replacement.

Keywords: *COP, GWP, Heat Pump, ODP, R290*

1.0 Introduction

The need for Heating, Ventilation and Air Conditioning (HVAC) for human comfort continues to grow. To improve human comfort, Air Conditioning (AC) and heat pump technologies have matured and become widely available solutions for maintaining adequate indoor space even under fluctuating ambient temperatures. Heat pump air conditioning systems are versatile devices designed to regulate indoor temperatures and maintain comfortable

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environments by providing both heating and cooling applications. Here is an overview of the applications and mechanisms of air conditioning for heating and cooling. Kasera *et al*., conducted a thorough study of a solar milk refrigerator using R290 refrigerant, focusing on various performance indicators such as Solar Coefficient of Performance (COP) and cooling capacity for a 14kg milk load. Their outcomes discovered a direct correlation between temperature increase and a decrease in cooling capability, coupled with a rise in electricity consumption[1]. As anticipated, the COP exhibited a decline with rising temperatures, diminishing from 0.61 to 0.23. In particular, milk refrigerators are designed to meet both heating and cooling requirements. Ketwong et al. conducted an Energy Efficiency Improvement (EER) study to investigate the potential of Direct Evaporative Cooling (DEC) as a means of cooling air conditioning condensers and generating cold air for space cooling[2]. The key study found that DEC is more effective in humid climates, while air cooling is more effective in hot regions. After experiments, it was observed that the mass ratio of feed water to circulating air decreases when the feed water temperature exceeds the wet bulb temperature of the air and the ambient temperature decreases. Tian Q *et al*. conducted a study of the mixed refrigerant R32/R290 (67%/33%) as a replacement for R410A in residential air conditioning systems[3]. They conducted theoretical and experimental studies on the performance of air conditioners using both R290 / R32 and R410A and found that the GWP of R410A was only 22%. Experimental data showed that the refrigerant charge was reduced by 30.0%-35.0% and both heating and cooling performances were significantly improved by 15.0%-24.7%. Zhang *et al*. comprehensively investigated the theoretical simulation and performance evaluation of R290, R744 and their commonly used mixture within the auto-cascade refrigeration cycle in their research. R290 and R744 show promise as refrigerants, but R744's high pressure and low-temperature demand stringent equipment[4]. Nawaz *et al*.[5] found that propane and ammonia are promising alternatives to R134a and R410A in terms of efficiency. The application of the entropy generation approach to a Ground Source Heat Pump (GSHP) system and its thermodynamic analysis have been presented by Lucia *et al*[6]. The validation of GSHP technology is progressing rapidly. Typically, the COP is in the range of 3 to 3.8. Calculations show that the seasonal average energy efficiency of a geothermal heat pump is about 70%, indicating a large optimisation potential. Moreover, optimising the entropy generation can reduce the system installation cost by 6.5%. According to a study by Byrne P *et al*., a heat pump that simultaneously heats and cools and uses the same electrical energy for generating chilled and hot water can reduce operational costs and greenhouse gas emissions[7]. The heating and cooling system can reduce the power losses of the air-to-water heat pump at low ambient temperatures by switching between the air and water evaporators during the defrost sequence. This improves the functioning of the air evaporator, increasing the heating output without reducing it. The alternating sequence of defrosting and improving performance in winter worked more effectively in cold climates. Nevertheless, HFC heat pumps for space heating and cooling remain economical and energy-efficient[8]. Shin, D. U *et al*., conducted a study on the use of thermal storage tanks in simultaneous heating and cooling systems, considering the energy savings potential arising from different operating modes of heat pump systems. The results suggest that the use of a radiant heating and cooling system with a thermal storage tank as the final system of a simultaneous heating and cooling system can reduce heat losses during heat transport[9]. This allows the introduction of a smaller capacity heat pump, which can produce the same amount of heating and cooling energy while improving the efficiency of the heat source equipment. R290, on the other hand, has zero GWP and ODP qualities, resulting in reduced power consumption and environmental benefits[10]. The economic, thermal and environmental performance of a refrigeration system with a variable displacement compressor that contains R1234yf, R152a and R134a was investigated by Zhu *et al*[11]. Their investigations showed that by lowering the stroke at part load, conventional refrigerators and those fitted with a variable displacement compressor had a significant advantage in terms of energy savings, cost savings, and CO_2 emissions reduction. For instance, adjusting a refrigerator's stroke from 13mm to 10mm using a variable displacement compressor with R134a lowers power usage, overall expenses and CO_2 emissions throughout the refrigerator's life cycle by 85.9%, 58.1%, and 61.3%, respectively. Running costs account for 88% of the overall economic cost of operating a refrigerator with a variable displacement compressor

over its lifetime as indirect emissions account for the majority of these refrigerators' life cycle CO_2. Makhnatcha *et al.*[12] presented Lifetime Climate Change Performance (LCCP), a comprehensive methodology for quantifying the refrigerant's effect on overall system emissions over its lifetime. Nevertheless, the impact of newly accounted emissions is negligible and the LCCP is more complicated than the Total Equivalent Warming Impact (TEWI). TEWI is susceptible to a system's energy efficiency. Therefore, the most important factor to consider when determining a system's environmental impact is the refrigeration system's efficiency as demonstrated for each potential refrigerant. When adjusted within tolerable limitations, other characteristics have a less substantial impact on the comparative study of refrigerant choices based on TEWI[13]. From the above literature survey, the environmental benefits of refrigerants R152a, R290 and R1270 in heat pumps are all comparable. Although many refrigerants are utilised for heat pump air conditioning, they are typically used independently for heating and cooling, with only R32 refrigerant now used for both applications. A comparison of several refrigerants, such as R32, R134A, R410A, R22 and R290, has not yet been conducted[14]. In this study, experimental measurements of the R290 heat pump were performed and compared based on parameters such as refrigerant mass flow rate, LCCP, TEWI, Coefficient of Performance Heating (COP_h), Coefficient of Performance Cooling (COP_C) atmospheric lifespan, GWP, ODP and power consumption in comparison to R32, R134A, R410A and R22 refrigerants under nominal conditions and Integrated Part Load Values (IPLV)[15]. Furthermore, comparison tests between heat pumps using the refrigerants mentioned above were performed using Ph charts and validated with the CoolPack software. These findings provide useful information for the research and development of R290 air-source heat pump systems in both cold and hot climates.

2.0 Heat Pump Description

Heat pumps provide similar functions to an air conditioning system in terms of refrigerant condensing in the condenser and boiling in the evaporator, pressure increase and drop and refrigerant flow throughout the system. As the role of the coils changes from heating to cooling using a four-way valve, it is easier to distinguish them as "indoor coil" and "outdoor coil" than it is to distinguish between condenser and evaporator coils. A volatile liquid called the working fluid or coolant flows throughout the system[16].

Figure 1[16] explains how a heat pump works. When the air conditioner is in heating mode, heat from the outside air is absorbed by the evaporator and the refrigerant is converted from a low-pressure liquid to a low-pressure gas. Heat is transferred from the heat source to the liquid working medium and as long as the temperature of the liquid working medium is lower than that of the heat source, the working medium will evaporate. A compressor is then used to compress the low-pressure gas to produce

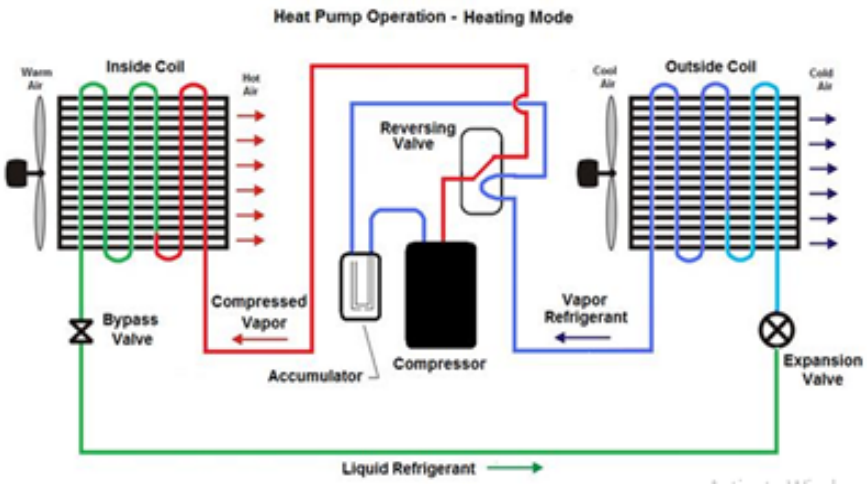


Figure 1. Heat pump air conditioning system in the heating mode[16].

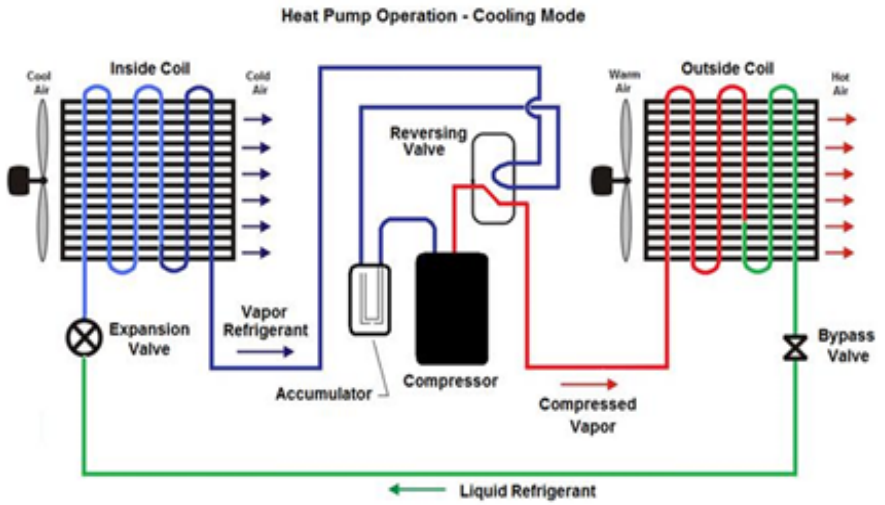


Figure 2. Heat pump air conditioning system in the cooling mode[16].

high-pressure gas. Heat is released from the compressor and dispersed throughout the house via the internal coil or condenser. The vapour condenses into a high-pressure liquid as heat is released. After leaving the inside unit, the liquid flows via an expansion valve, where it expands from high pressure to low pressure and the cycle repeats.

The operation of a heat pump air conditioning system in cooling mode is shown in Figure 2,[16] which also demonstrates how the cooling cycle is the opposite of the heating cycle. The reversing valve is activated during the cooling mode, which reverses the flow direction of the refrigerant. In this mode, heated air passes over the internal coil, which is the evaporator and gathers heat, which is then released into the atmosphere by the exterior coil. The only thing that changes when the heat exchanger coils are in the cooling or heating mode is the operation of the refrigerant cycle[16]. The P-h (pressure, enthalpy) diagram that follows, which is mentioned in Figure 3, displays the properties of different refrigerants with pressure on the vertical axis and enthalpy on the horizontal axis[17].

Condensation is the state transition from gas to liquid and evaporation is the state transition from liquid to gas. Saturation is the boundary of any transition, and saturation temperature is the temperature at which saturation occurs. The kind and pressure of the refrigerator affect temperature saturation. The saturation curve, often known as the P-h diagram for different refrigerants, displays the saturation temperature features[18]. The P-h

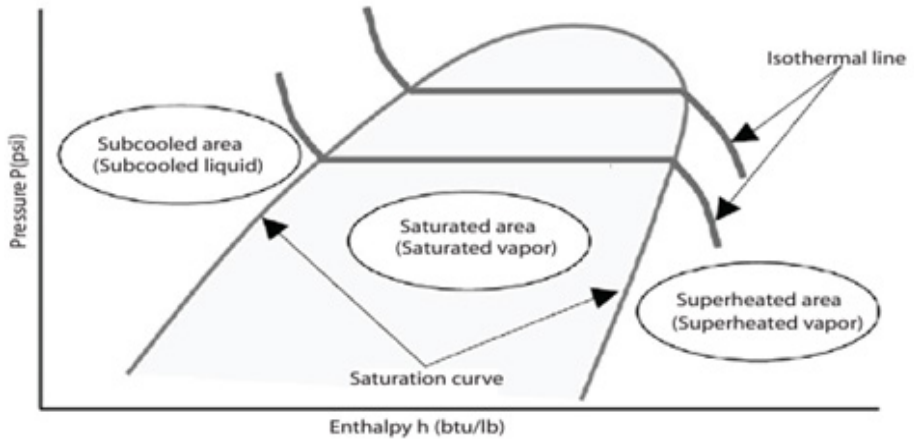


Figure 3. Ph chart of heat pump air conditioning system for various refrigerants[17].

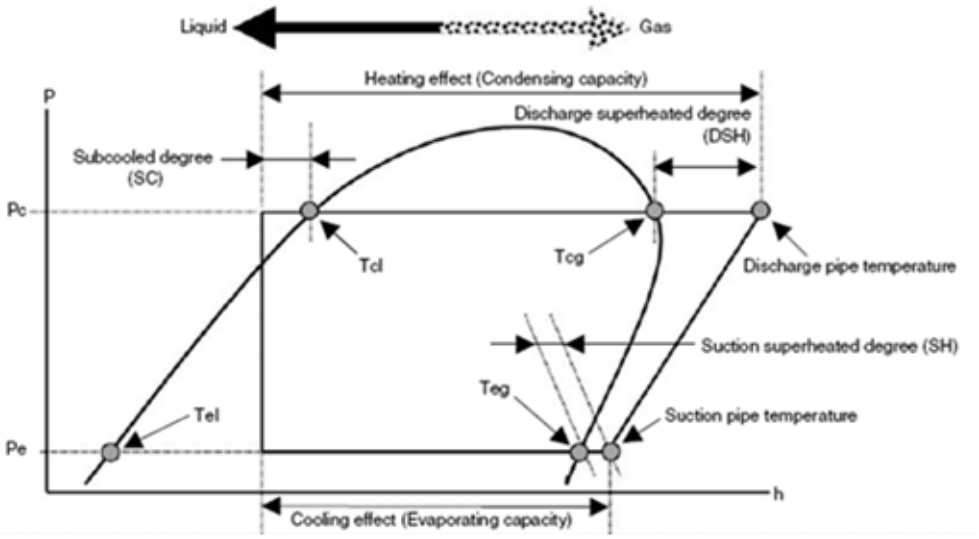


Figure 4. Ph chart of heat pump air conditioning system for various refrigerants for heating and cooling[17].

diagram displays what are known as isotherms, which are the temperature gradient characteristics of pressure and enthalpy. The nature of the refrigerant can be determined by dividing the area by the saturation curve that contains the point where pressure and isotherms connect. By taking a single measurement of the refrigerant's temperature and pressure, the above intersection point can be found. Three categories are used to categorise the refrigerant's state: The condition in which the refrigerant is in the gaseous state of saturated vapour is known as superheated vapour. The refrigerant is in liquid condition when it comes to the mixing of liquid and gas, also known as supercooled wet liquid[19].

The properties of several refrigerants are displayed in the P-h diagram that follows, with enthalpy on the horizontal axis and pressure on the vertical axis. Figure 4 illustrates a theoretical refrigeration cycle for heating and cooling that ignores pressure loss[17-19].

3.0 Mathematical Model

Any refrigeration system design must start with an estimation of the heat load. Let's say for the sake of convenience that our fictitious refrigerated room needs a cooling capacity of 3.5kW (Qroom). The temperature at which this 3.5 kW of heat must be absorbed will also need to be known. Depending on the application, the refrigerant fed into the evaporator will evaporate at a different temperature. Different systems require different evaporation temperatures, including freezing, blast freezing and chilling. With 3.5kW of refrigeration capability, cooling would require 3.5kJ of energy to be absorbed from the room each second at the necessary evaporation temperature. To rephrase the previous sentence, (Qroom) Would stand for the amount of heat (kW) that the evaporator will absorb from the room. A refrigerant needs to be introduced into the evaporator at the proper flow rate to remove this heat from it[14].

The equation below (1) describes how the heat transfer relates to the flow of refrigerant:

$$Q_{ref} = \dot{m}_{Ref} \times \Delta h \quad (1)$$

Where,

Qref – Rate of heat that can be absorbed by a refrigerant kW, - the mass flow rate of refrigerant supplied to the evaporator kg/sec, Δh – Enthalpy change at the specified evaporating temperature, kJ/kg. To calculate the Q_{ref} the amount of refrigerant entering the compressor the Rota meter is used.

$$Q_{room} = Q_{ref} \quad (2)$$

Where, Amount of heat liberated inside the room.

Q_{room}= = Amount of heat transfer by the refrigerant.
Combining equations (1) and (2) we get,

$$Q_{room} = \dot{m}_{air} \times \Delta h \quad (3)$$

From Equation (3) it is clear that the cooling capacity of the evaporator is dependent on the 2 factors.

When it comes to the amount of air conditioning used, the room size as well as the number of people present in the room is an important parameter which affects power consumption. Accordingly, the capacity of the AC depends on the number of people and the size of the room. For example, a room with 20 to 25 people needs multiple ACs while a room with 3 to 5 people needs only one. AC power consumption will increase as the room size increases. Likewise, smaller rooms do not use more AC power[15].

3.1 Trade-Off Relationship Between GWP and Flammability

One of the most important issues is switching from HFCs to lower GWP refrigerants to limit the emission of greenhouse gases, particularly HFCs, from refrigerating and air-conditioning equipment. Much lower GWPs than R410A are found for R1234yf, R32, R717 and R290. R1234yf, R32, and R290 are flammable while R410A is not. R1234yf and R32 are considered to be mildly flammable and fall under the American Society for Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) A2L class because their burning velocities are less than 10cm/s[16]. According to ASHRAE standards, the flammability limit is one of the most important factors when selecting a refrigerant for a heat pump or air conditioner. A detailed comparison of the Lower Flammability Limit (LFL) and Upper Flammability Limit (UFL) of various refrigerants is shown in Table 1.

3.2 Thermal and Physical Properties of the Refrigerant

The performance of a refrigerator is expressed by the coefficient of performance, which is the ratio of the heat absorbed by the cold object to the work produced by the compressor. The performance of the system is evaluated as follows:

The effort per kilogram of refrigerant, expressed in terms of isentropic compression, is given by

$$W_c = m_r (h_2 - h_1) \quad (4)$$

The refrigerant effect, i.e. the heat absorbed or removed by the liquid vapour refrigerant during evaporation, is calculated and displayed for each kg of refrigerant.

Table 1. The Lower Flammability Limit (LFL) and Upper Flammability Limit (UFL) of the refrigerant

Properties	Unit	Refrigerant				
		R290	R32	R410A	R717	R1234yf
Boiling Temperature,	°C	-41.1	-49.8	-50.9	-34.3	-30.1
Critical Temperature,	°C	96.7	77.2	70.8	132.4	94.7
GWP (100 years)	-	<3	675	2088	<1	4
Burning Velocity	(cm/s)	38.7	6.7	-	7.2	1.5
LFL	[vol%]	1.8	13.3	-	15	6.2
UFL	[vol%]	9.5	29.3	-	28	12.3
Minimum Ignition Energy	(mJ)	0.246	15	-	21	500
Flammability	-	3	2L	1	2L	2L

$$Q_e = m_r (h_1 - h_4) \quad (5)$$

The Coefficient of Performance (COP) is the ratio of heat removed from within the refrigerator to the work done in the refrigerator.

$$COP = \text{Refrigeration Effect/ Work Done} \quad (6)$$

$$COP_C = h_1 - h_4/h_2 - h_1 \quad (7)$$
$$COP_h = h_2 - h_4/h_2 - h_1$$

To calculate the COP and refrigerant effect, the cooling and heating capacity of the heat pump is to be calculated from the compressor work and power consumption by the compressor to provide the cooling/heating capacity inside the room.

$$\text{Pressure Ratio} = P_C/P_e \quad (8)$$

$$EER = 3.5 \times COP \quad (9)$$

$$\text{Capacity of the system} = 1\ TR = 3.5\ kW \quad (10)$$

$$\text{Heat rejected in the condenser} = m_r \times (h_2 - h_3) \quad (11)$$

$$\text{Heat absorbed in the evaporator} = m_r (h_1 - h_4) \quad (12)$$

Where,

The compressor's input and exit refrigerant enthalpies or h1 and h2, are expressed in kJ/kg.

The refrigerant enthalpies at the input and output of the expansion valve are expressed as h_3=h_4 kJ/kg.

Under the following operating conditions, the system's performance for the air conditioning system with a 1 TR capacity can be calculated as follows:

The condenser temperature of 54.5˚C and the evaporator temperature of 16˚C has been selected as the operating parameters for a vapour compression cycle with three distinct types of refrigerants (R290, R32, R134A, R401A and R22)

4.0 Numerical Analysis

With the selected refrigerants as working fluids for the vapour compression refrigeration system, a thorough analysis of the system performance evaluation was carried out, focusing on the influence of evaporation and condensation temperatures. This was done using the Cool Pack software and the theoretical results of the pH chart. The simulation of the system with R290 showed better performance than the other refrigerants considered in this study in terms of the influence of condensation temperature on the cooling performance of the system. Furthermore, the simulation results as shown in the figure state that the performance of the system with R134a is comparable to that of the systems with R32 and R22. It is noteworthy to emphasise that, in comparison to the other refrigerants taken into consideration in this study, R290's performance evaluation simulation findings show a higher refrigerating effect. These findings support the theory behind the system's improved performance when R290 and other refrigerants are used, as demonstrated[20,21].

The behaviour of the main components of a single-stage vapour compression refrigeration system can be accurately predicted by applying the proposed mathematical model using the Ph diagram. The components of the system are the evaporator, the condenser, the expansion valve (capillary tube) and the compressor. The simulation model shown in Figure 5 supports the following possibilities:

There is a steady-state operation of the refrigeration system. (ii) The compressor, condenser, and evaporator's irreversibility are ignored. (iii) Frictional pressure drops are not taken into account. (iv) There is very little heat loss to the environment as the refrigerant passes through the condenser and evaporator heat exchangers at a steady pressure. It is assumed that the compression process is isentropic[22]. The information flow diagram in Figure 4 shows the model's solution algorithm. The software requires the kind of refrigerant, product attributes, evaporation temperature and condensation temperature as input data. The selected refrigerants' thermodynamic parameters (P, h, v and s) are taken from the COOLPACK saturation table. The first simulation focused on the thermodynamic properties of R12. Then, further simulations were performed by integrating the corresponding thermodynamic parameters of each refrigerant, such as ammonia, R22, R134a, R600a and R290. In particular, considering equations 1-8, the model allows the evaluation of the impact of the number of refrigerated items on the operation of a

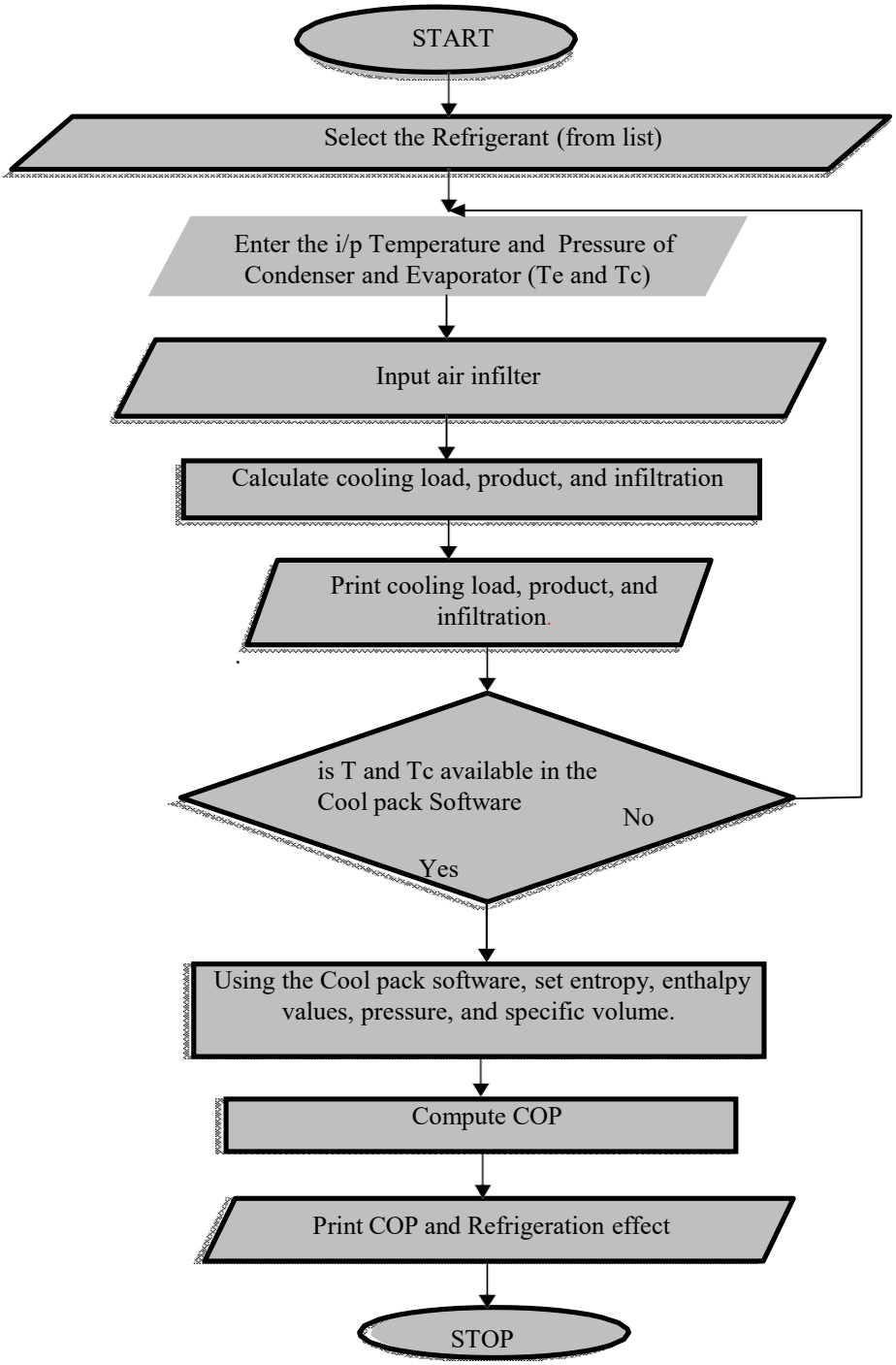


Figure 5. Flow chart of the simulation program using cool pack[20,21].

vapour compression refrigeration system. As a result, the established model facilitates the performance estimation and optimal design of the refrigeration system[23,24]. The performance evaluation of the system based on the simulation method for each refrigerant includes the calculation of the COP. This quantitative measurement provides information about the efficiency and effectiveness of the vapour compression refrigeration

system, allowing informed decisions to be made when optimising its design and operation[25].

$$COP = {}^{Qe}/_{Wc} \quad (13)$$

Equation no 12 explains the COP of heat pumps and air conditioning systems. The ratio of the amount of heat absorbed by the evaporator and the amount of heat rejected by the condenser is the COP.

5.0 Results and Discussions

For the theoretical investigation, when the vapour refrigerant was in a dry saturated condition at the beginning of the compression, the following properties were obtained using the R290 P-h chart. The results were validated through the Cool Pack Software. By referring to the above formula for the Refrigerant R32, R134A, R410A and R22 just as the procedure to calculate the various factors which are calculated for the R290, we have calculated all the factors for other refrigerants like R32, R134A, R410A and R22. After calculating the COP for Cooling and heating theoretically by using the P-h chart, the same results are validated for COP using the Cool Pack Software student's version (Free software)[16]. The one-stage cycle analysis is done for the Dx evaporator which is used in the heat pump for heating and cooling using refrigerant R290 as an indoor device, which is shown in the figure. The parameters are the same as using the Ph chart. The calculated values are validated through a cool pack. The results are shown in Figure 6.

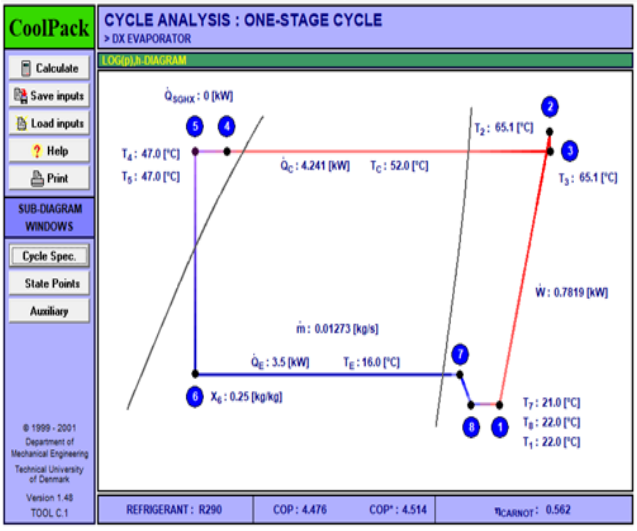


Figure 5. One-stage cycle for R290 refrigerant using a cool pack.

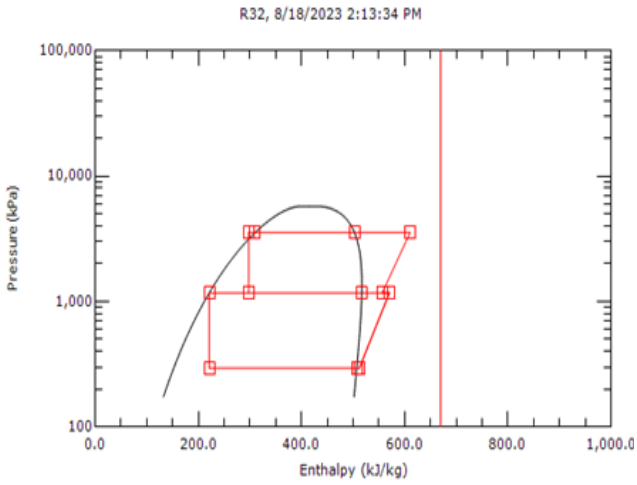


Figure 7. Pressure enthalpy chart for R32 refrigerant using cycle DHX.

A single-stage cycle analysis was carried out for a Dx evaporator used in a heat pump for heating and cooling with R22, R410 and R134a refrigerants as indoor units. The procedure and methodology used above for R290 is repeated for refrigerants R22, R410 and R134a for heat pump heating and cooling systems. The results are shown in the graph in Figure 6.

As the details cycle analysis of R32 Refrigerant for the heat pump air conditioning is not available in the cool pack tool. So we have used the cycle DH tool for the analysis of this refrigerant. The procedure is the same as we followed in the cool pack tool.

The one-stage cycle analysis is done for the Dx evaporator which is used in the heat pump for heating and cooling using refrigerant R32 as an indoor device. The procedure and method used for R32 is refrigerant for heat pump heating and cooling system and results are shown on the graph presented in Figure 7 using the cycle DHX tool.

For selecting the refrigerant in any of the heat pump and air conditioning systems as well as the HVAC system the thermal and physical properties are very important parameters. The detailed thermal and physical properties of different refrigerants are discussed in Table 2.

Table 2. Physical and thermal properties of various refrigerants

Refrigerant	Chemical Formula	Atmospheric life in Year	GWP	ODP	Refrigerant Mass Flow (kg/s)	Power (kW/ TR)	TEWI kg CO2-eq	LCCP, kg CO2-eq	COP_C	COP_{Ch}
R290	C3H8	0.041	20	0	0.0119	1.194	35,124.13	37,342	4.389	4.47
R32	CH2F2	4.9	677	0	0.0189	1.03	39,458	41,342	3.36	3.98
R134A	CH2 FCF3	13.8	1,300	0	0.006	0.684	36,629.80	40,125	3.23	4.43
R410A	-	17	2,088	0	0.0304	1.064	41,978.29	44,787	3.28	4.28
R22	CHClF2	12	1,700	0.055	0.0244	0.976	38,506.10	41,576	3.4	4.36

6.0 Analysis of 290 Refrigerant Compared to Other Refrigerants

R290 burns more easily than R32, but its energy release is relatively smaller and the post-combustion products are not toxic. R32 burns with more difficulty than R290, its release energy is relatively larger and the post-combustion product (hydrogen fluoride) is highly toxic.

In this paper, we have considered the various parameters and properties of the various refrigerants for the HPAC system to calculate the COP of the system. Considering the standard conditioning we have calculated the COP of the system for various refrigerants using the Ph chart and taking into the same consideration we have compared the COP with the CoolPack simulation tool. We have received some changes in the theoretical COP. The Comparison between theoretical and simulation is mentioned in Table 3.

7.0 Conclusion and Future Work

Using R-290 refrigerant, the heat pump unit is converted to an air conditioning system and the performance of the new system is evaluated. The main findings of the study are summarised as follows:

- The present work monitors and evaluates the compressor power consumption and COP values at various load levels throughout the test period to determine the appropriate refrigerant charge in the refrigeration system.
- The use of R290 contributes to promoting the "go green" movement, aiming to reduce the risk

Table 3. Thermal and physical properties of different refrigerants

Refrigerant	Chemical Formula	using Ph-Chart	COph using coolpack software	using CoolPack Software	Ph- Chart	Difference between Theoretical and Simulation COP
R290	C3H8	4.389	4.47	4.4	4.45	0.1
R32	CH2F2	3.36	3.98	3.36	4.36	0.8
R134A	CH2FCF3	3.23	4.43	4.126	4.162	0.23
R410A		3.28	4.28	3.658	3.724	0.5
R22	CHClF2	3.4	4.36	4.10	4.132	0.10

of ozone layer depletion and global warming. Combining the heat pump with the R290 provides significant energy savings and increased cooling capacity.

- Industrial processes to increase cooling and heating efficiency and effectiveness with heat pump-controlled air conditioning systems which is carried out using the applied scientific method outlined in this article.
- A heat pump for simultaneous cooling and heating was created to produce domestic hot water while simultaneously heating and cooling small residential and office buildings.
- R290 is a natural refrigerant with very low long-term global warming potential. Increase C.O.P. reached 22.92%, 19.12% and 15.84%.
- Power usage was reduced by 58.69%, 42% and 47%.
- The discharge temperature was reduced by 23°C, 24°C and 25°C, respectively.
- R290 has a great affinity to perform better domestic performance, as the amount of refrigerant is limited to 500g. Further research is needed to increase the amount of refrigerant and applications provided for commercial purposes to save our environment with higher security features.

8.0 Acknowledgements

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8.1 Availability of Data and Materials

All data used to support the findings of this study are included in the article.

8.2 Author Contributions

All data and work included in the manuscript have been provided by the authors.

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