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Dynamic Simulation of Vapor Compression Refrigeration System with R134a and R1234yf using Dymola Behavior Modeling

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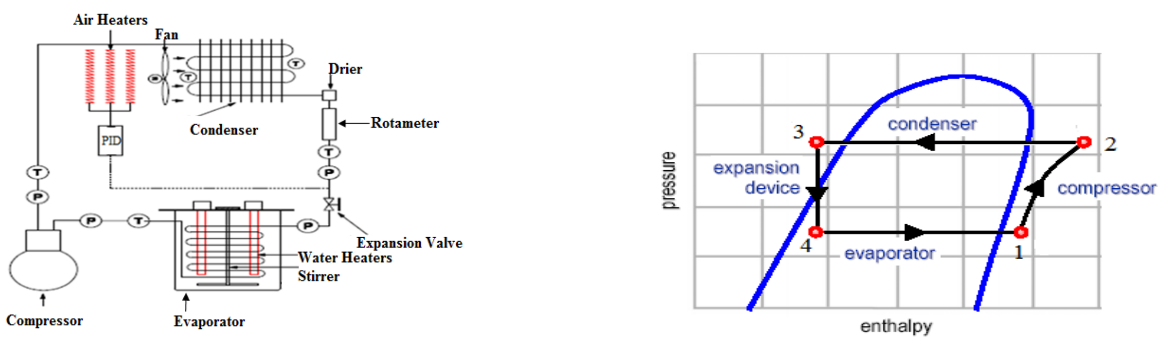
Abstract **–** Refrigeration and air conditioning is vital part of the human life. Heating, ventilating, air conditioning and refrigeration (HVACR) industries are consuming one third of the world's high-grade energy for cooling, heating, comfort, residential and industrial applications. Dymola Behavior Modeling from 3DEXPERIENCE, Dassault systemes, is a multidomain simulation tool for transient and steady state applications. In the present work, the components from the free Modelica library (Thermal, Fluid Flow, Heat Transfer) and Thermal System 1.6 commercial library from Dymola are considered for the simulation of refrigeration system with multiport extruded condenser and evaporator with R134a and R1234yf as refrigerants alternately. The dynamic simulation of vapor compression refrigeration system with R134a and R1234yf is performed and analyzed the system in terms of refrigeration effect, compressor work consumption, condenser capacity and coefficient of performance. It is found that the compressor with R1234yf has 13.19% less power consumption than R134a for the same parameters of evaporator, compressor, condenser, expansion valve with the same solver controls. The refrigerating and condenser capacity of R1234yf is smaller by 5.7% and 9.57% than R134a respectively. Thus, the coefficient of performance (COP) of R1234yf is more than 8.67% than conventional R134a refrigerant. For performing the simulation, Dymola Behavior Modeling is used from 3D EXPERIENCE R2021 Dassault Systemes for dynamic simulation of refrigeration system.

Keywords**:** Dymola, Modelica, R1234yf, Thermal system, 3DEXPERIENCE

1. Introduction

The fossil fuels are depleting fast so need to develop the energy efficient technologies with globally friendly refrigerants. The vapor compression refrigeration system (VCR) is mostly used in world for HVACR applications over vapor absorption and adsorption refrigeration systems [1-3]. The performance of the VCR system is dependent on the steady and transient condition of compressor and other important components such as condenser, evaporator and expansion valve. In the present research, R1234yf refrigerant which is having global warming potential (GWP) of just 4, is used in the dynamic simulation of refrigeration system using Dymola Behavior Modeling from Dassault Systemes over R134a which has a GWP of 1430 which is quite high as per the environmental standards. The Dymola (Dynamic Modelling Laboratory) software tool which is based on free Modelica library for developing the multi-physical models. The Dymola from the 3DEXPERIENCE is suitable to simulate multi-physics models when experiments are costly, dangerous for the human being as well as the system required for the performance of the experiment is not available. The companies from the HVACR, Mechanical, Electrical and other domain are using the Dymola simulations for predicting the performance before manufacturing the components. The modelling and simulation of refrigeration and air conditioning system is important for design, development of VCR system for proper control and testing the performance, estimate the dynamic behavior in terms of cool down time, start-up, pressure gradients, torque at the compressor, design of different type of heat exchangers, forecasting the compressor power consumption and system coefficient of performance. Thus, due to the drawback of the experimental methods, model is developed and the performance is investigated in advance and corrective actions are initiated. It is to be kept in mind that if the model developed is not based on the practical approach, it will produce wrong conclusions. It is therefore necessary to compare the results of the simulation with the experimental system. Thus, while performing the simulation, critically analyze the assumptions and estimates with sensitivity analysis. The dynamic models are time dependent and static model implies the steady state condition of the system.

Modelica is a high-level modeling language which allows mathematical modelling of complex systems for dynamic simulation where as in other simulation technique such as computational fluid dynamics, a single component need to simulate at a time. Modelica is an object-oriented equation-based programming language, oriented toward computational applications with high complexity requiring high performance. Modelica is primarily based on equations instead of assignment statements which allows acausal modeling. Modelica has multidomain modeling capability which can group the components from various domains such as mechanical, electrical, hydraulic, thermal and control system [4]. Thus, the modelling and simulation of refrigeration system is significant for optimum refrigerant charge, development of combined systems for heating and cooling, selection of components, including refrigeration system as a subsystem of air conditioning system of automotive, buildings, aircrafts etc. Thermal mobile air conditioning is a commercial library in Dymola Behavior Modelling used for dynamic performance. The aim of this research is to predict the performance of the VCR system for the same parameters of compressor, condenser, evaporator and expansion valve with R134a and R1234yf. The compressor is the heart of the VCR system compressing the refrigerant from evaporator pressure to condenser pressure. The compressor used may be reciprocating, rotary, centrifugal, axial, screw or scroll compressor depending upon the specific application and capacity. The working substance in the VCR cycle is the refrigerant which is the heat carrying medium. The selection of refrigerant is depending on the thermodynamic, chemical, physical and environmental properties such as ozone depletion potential, global warming potential and atmospheric life time. Ooi studied the compressor performance using R134a and R1234yf and concluded that the compressor with R134a performed better in the high condensing and low evaporative temperature whereas R1234yf is better for low condensing temperature than R134a with difference in refrigerating capacity of 5% and COP by 10% respectively [5]. The heat is absorbed in the evaporator producing refrigerating effect as per the application is produced by maintaining desired pressure and temperature in the evaporator. The evaporator may be dry expansion type or flooded type. The condenser is rejecting heat equivalent to heat absorbed in the evaporator and heat produced due to mechanical compression. The condensers can be classified as air cooled, water cooled and evaporative cooled condensers. The expansion valve may be a capillary tube or thermostatic expansion valve, electronic expansion valve depending the application it can be selected. Figure 1 shows the schematic diagram and P-h diagram for VCR system. The natural refrigerant, Carbon dioxide (R744) is having GWP of 1, suitable for mobile, automotive and transport refrigeration and air conditioning by controlling the leakage due to high pressure in the system due to it lower critical temperature [6, 7]. Equations (1) to (4) shows the performance parameters of the VCR system.



(a) (b)

Fig. 1: (a) Schematic diagram and (b) P-h diagram for VCR system.

$$\text{Power Consumption} = mr\,(h2 - h1) \tag{1}$$

$$\text{Refrigeration capacity} = mr\,(h1 - h4) \tag{2}$$

$$\text{COP} = \frac{(h1 - h4)}{(h2 - h1)} \tag{3}$$

$$\text{Condenser capacity} = mr\,(h2 - h3) \tag{4}$$

Where-

h1- Enthalpy of superheated vapor at compressor inlet (kJ/kg), h2- Enthalpy at compressor discharge (kJ/kg), h3=h4- Enthalpy at condenser exit (kJ/kg) and mr is the mass flow rate of refrigerant.

2. Refrigeration System

The commercial refrigeration library from Dymola Behavior Modelling is considered for the dynamic and steady state simulation by connecting different physical base components. This library is prepared from free Modelica library from Thermal, Fluid and Heat Transfer libraries [8-10]. In Dymola library, models are designed and developed for system level simulation, one dimensional, one-two-phase flows with conservation of mass, momentum and energy. In one dimensional system simulation, finite volume method of discretization is used [11]. The conservation of mass and internal energy for control volume is written as Eq. (5) and Eq. (6).

$$\frac{dM}{dT} = m^{\cdot}_{in} - m^{\cdot}_{out} \tag{5}$$

$$\frac{dU}{dT} = m^{\cdot}_{in} h_{in}^{\cdot} - m^{\cdot}_{out}\, h_{out}^{\cdot} + Q^{\cdot} + W^{\cdot} \tag{6}$$

The VCR cycle is represented in Fig. 2 for refrigeration cycle using conventional refrigerant R134a and alternative R1234yf refrigerant. The model is prepared by selecting and joining the components with the simulating parameters. The system is made up of different components such as compressor, condenser, evaporator, expansion valve with pressure and temperature measuring sensors. The condenser and the evaporator used are multiport extruded heat exchangers which are efficient and one fifth compact than conventional condensers. The condenser pressure depends on the ambient temperature whereas the evaporation pressure and temperature depend on the desired cooling temperature to be maintained in the compartment. The temperature of the cool air is controlled by the PI controller and the compressor speed. The superheating at the inlet to the compressor is maintained with the thermostatic expansion valve [12, 13].

2.1. Compressor

The reciprocating compressor model is used with a variable displacement considering the physical losses that occurred during the compression. The model used is successfully calibrated with measurement data of a specific compressor. The specific compressor model can be selected from the library as per the application. The pressure drop at the suction and discharge side and internal losses are considered. The important values of the compressor model considered are displacement volume of 150 × 10^-6 m^3, frequency 50 Hz, ambient temperature of 293.15 K and atmospheric pressure as 1 bar, mass flow rate of refrigerant as 0.05 kg/s. The volumetric and isentropic efficiency of compressor considered as 80% respectively [14, 15, 16].

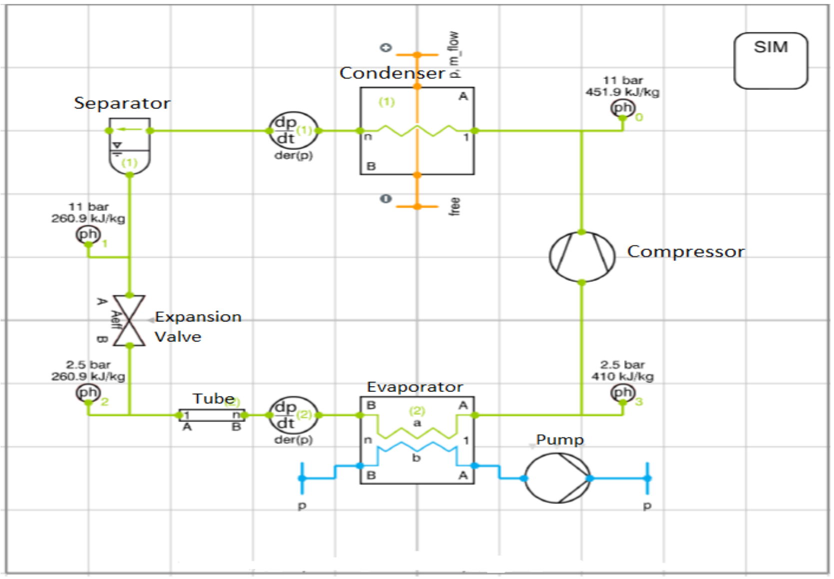


Fig. 2: (a) Schematic model of refrigeration cycle in Dymola.

2.2. Condenser

The condenser used is multiport extruded cross flow type as it is efficient and compact heat exchanger. Three passes are provided considering the pressure drop and heat transfer coefficient with the aluminum as material. The heat transfer model used for tube side is Shah Chen Gnielinski Dittus-Boelter and pressure drop as Swamee Jain with tube roughness value of 0.0001. Fin side heat transfer and pressure drop model is considered in the simulation [17, 18].

2.3. Separator

The separator model separates the vapor refrigerant at the inlet port into a liquid and a gas phase. The model has a replaceable function for the separation characteristic. The outlet conditions for the port gas and port liquid can be calculated either estimating an ideal separation or with a user-defined function. It is found that if the filling level is between 10% and 90%, the port gas and port liquid provide pure gaseous and pure liquid conditions respectively. These parameters can be changed and the performance can be estimated. If the filling level is lower than the liquid outlet smooth level (10%), the port liquid provides a mixture of gaseous and liquid conditions dependent on the filling level. If the filling level is higher than the gas outlet smooth level (90%), the port gas provides a mixture of gaseous and liquid conditions dependent on the filling level [19].

2.4 Expansion Valve

A thermostatic expansion valve (TXV) regulates its constriction corresponding to the pressure and temperature of a refrigerant flow as per the desired temperature in the evaporator. The TXV model is based on the Bernoulli equation which is used to calculate the mass flow rate through the valve. Therefore, the model considers an effective flow area of the expansion valve. The effective flow area resembles the smallest cross-section area in the valve. The effective flow area is calculated in relation to the pressure of the refrigerant flow at the inlet and outlet. The opening pressure describes the pressure of the refrigerant at which the opening force of the valve is in equilibrium with its closing force. The relation between the pressures and the effective flow area is described by the parameter beta (β) which therefore can be described as pressure differential flow area [m^2/Pa] in Eq. 7. With increasing pressure or temperature of the refrigerant flow, the effective flow area asymptotically approaches a maximum value, due to the geometrical limitations of the valve. The model considered the thermal inertia of the physical valve by using a time constant. The time constant sets the temperature at the bulb as differential state. A typical value for time constant is 60 s [20, 21, 22].

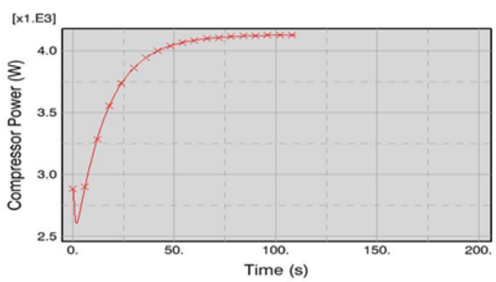
$$A\ eff. = \beta\ (P_{open} - \mathrm{P}_{evapout}) \tag{7}$$

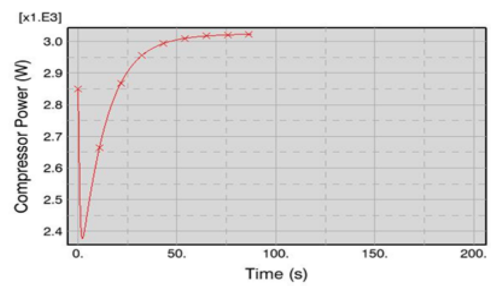
2.5. Evaporator

Evaporator used is multiport extruded cross flow type with aluminium as material. The tube side heat transfer model used is Steiner Shah Gnielinski Dittus-Boelter considering the fin efficiency and pressure drop model from Dymola documentation.

3. Results and Discussion

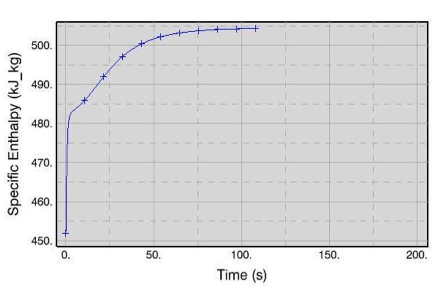
The pressure, temperature and enthalpy values are observed at various salient points across the compressor, condenser, expansion valve and evaporator to find the performance of VCR system in terms of refrigeration effect, compressor work consumption, condenser heat rejection and coefficient of performance for R134a and R1234yf in transient condition. Figure 3 (a) and (b) shows the compressor power consumption for R134a and R1234yf up to the steady state condition. Figure 4 (a) and (b) represents enthalpy values at the compressor discharge for R134a and R1234yf respectively which indicated less value or R1234yf than R134a. It is found from the Fig. 3 that the compressor with R1234yf has 13.19% less power consumption than R134a for the same experimental and solver parameters at the steady state condition. The Table 1 shows that refrigerating and condenser capacity of R1234yf is lesser by 5.7% and 9.57% than R134a. Thus, coefficient of performance of R1234yf is more than 8.67% than conventional R134a refrigerant. Table 1 shows the comparative performance of R134a and R1234yf in the transient condition.

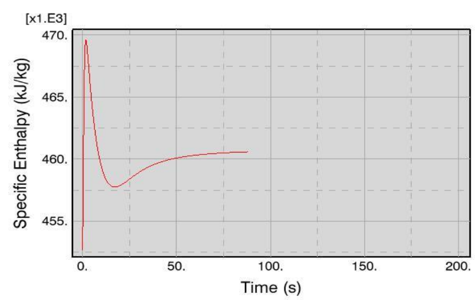




(a) R134a (b) R1234yf

Fig. 3: (a) (b) Dynamic compressor power in Dymola.





(a) R134a (b) R1234yf

Fig. 4: Specific enthalpy at compressor discharge, kJ/kg.

Table 1: Transient performance comparison of R134a and R1234yf using Dymola.

Refrigerant	Enthalpy h1 (kJ/kg)	Enthalpy h2 (kJ/kg)	Enthalpy h3=h4 (kJ/kg)	Compressor Work (kJ/kg)	Refrigerating Effect (kJ/kg)	Condenser Capacity (kJ/kg)	COP
R134a	417.9	504.3	337.2	86.4	80.7	167.1	0.934
R1234yf	385.6	460.6	309.5	75	76.1	151.1	1.015

4. Conclusion

After performing the simulations using Dymola Behavior Modeling from the 3DEXPERIENCE Dassault Systemes, it is found that Modelica language is useful as a mathematical equation base models in different domains. The Modelica 4.0 free library is used along with the Thermal System commercial library from Dymola. The simulation of the entire VCR system with multiport extruded condenser and evaporator, compressor and expansion valve are performed with R134a and R1234yf alternately. It is found that COP with R1234yf is 8.67% more than R134a without changing the other parameters.

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