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Performance Analysis of Exhaust Heat Driven Automotive Air-Conditioning System

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ABSTRACT

Existing automobile engine losses lots of heat through exhaust gas. In this vapour absorption system exhaust heat is used as heating source of vapour absorption system. From the literature it is observed that heat potential is sufficient for powering the proposed air conditioning system. The significance of the work is that it will provide space cooling for the passengers and thereby enhances thermal efficiency and reduces fuel consumption without affecting performance of the automobile. Further the vapour absorption cycle uses non CFC refrigerant and thereby have no effect on environment. The present work is focused towards the design and development of an air conditioning system for the automobile using waste heat from exhaust. Also, this system includes control system which varies the flow rate of solution in generator according to engine exhaust gas temperature as it varies according to load condition. Also, this research work includes study of thermodynamic and parametric analysis of Li-Br vapour absorption refrigeration system.

INTRODUCTION

Early air conditioning systems encountered a number of technological difficulties, and the start of World War II further impeded their advancement. Many of these problems were fixed by the 1953 model year, and automakers like General Motors and Chrysler reintroduced better air conditioning systems. What was once considered a luxury gradually became a necessity for everyday car owners. Initially, most air-conditioning components were installed in the trunk, occupying a significant amount of space. In 1953, the Harrison Radiator Division of General Motors introduced a major innovation by designing a compact system integrated within the under-hood and dashboard areas, eliminating the need for trunk installation. Around the same time, the use of desiccant materials to remove moisture from the refrigerant line was also introduced. The following years saw several important milestones in the continued development of automotive air-conditioning systems.

Automotive air-conditioning systems are essential for ensuring passenger comfort and enhancing safety during vehicle operation under diverse climatic conditions. By maintaining a controlled cabin environment, these systems help regulate temperature, humidity, and air quality, allowing occupants to remain comfortable even in extreme weather. Improved thermal comfort also contributes to driver alertness, reducing fatigue and enhancing overall driving performance, which indirectly supports road safety. Over the years, air-conditioning has evolved from being a luxury feature to a standard requirement in modern vehicles. With increasing urbanization, rising temperatures, and longer commuting times, the demand for efficient cabin cooling systems has grown significantly across all categories of vehicles, including passenger cars, commercial vehicles, and public transport systems.

Although air-conditioning systems significantly enhance passenger comfort, they have a dual impact on vehicle fuel consumption. First, additional fuel is required to operate the compressor. Second, the presence of air-conditioning components adds to the overall weight of the vehicle, increasing energy demand. Furthermore, the usage of air conditioning depends on climatic conditions and seasonal variations, with the most significant effect on fuel economy occurring during active operation.

CONVENTIONAL VEHICLE AIR CONDITIONING

The application of refrigeration and air-conditioning in transportation offers significant advantages. Air-conditioning systems are widely used in automobiles, as well as in railways and ships, to enhance passenger comfort. In recent years, automotive air conditioning has experienced rapid market growth. In a country like India, where hot climatic conditions persist for nearly 8 to 10 months each year, air conditioning has become increasingly essential. Modern vehicles are now designed to incorporate air-conditioning systems within the cabin as a standard or integrated feature.

The VCR cycle is highly preferred because of its simple design, compact size, high efficiency, and ability to achieve very low temperatures (Arora, 2004; Khurmi & Gupta, 2013). Modern refrigeration and air-conditioning systems mainly use this cycle due to its reliable and continuous cooling performance (Stoecker & Jones, 1982).

In a Vapour Compression Refrigeration (VCR) system, the refrigerant absorbs heat in the evaporator and evaporates (Arora, 2004; Khurmi & Gupta, 2013). The compressor increases its pressure and temperature. In the condenser, heat is rejected and the refrigerant condenses into liquid form. The expansion valve lowers its pressure and temperature before it re-enters the evaporator cycle (Stoecker & Jones, 1982).

Advantages

These control units ensure the safe and efficient operation of the air-conditioning system. The thermostat plays a key role in preventing frost formation on the evaporator coil while also maintaining the desired cabin temperature. When the evaporator fin temperature nears the freezing point, the thermostat responds by sending a signal to the control unit (thermo amplifier). The control unit then switches off the electromagnetic clutch, interrupting power to the compressor. This causes the compressor to stop temporarily, preventing ice formation on the evaporator and maintaining safe system operation.

Drawbacks

1.Since most concentrated, it is subject to higher wear and tear, which can also lead to increased noise.
2.The system consumes mechanical energy from the engine, which can reduce engine power, speed, and overall performance.
3.Operating costs are high due to increased fuel consumption, maintenance requirements, and the cost of refrigeration components. The use of air conditioning can reduce fuel efficiency by approximately 1 to 1.5 km per liter.
4.Leakage of refrigerants such as CFCs (chlorofluorocarbons) can cause significant damage to the ozone layer.
5.In vehicles with lower reserve power, the operation of the A/C system can negatively affect acceleration.

VAPOUR ABSORPTION REFRIGERATION SYSTEM

Unlike the vapour compression system, the VAR system is a kind of refrigeration system that runs on heat energy rather than mechanical labor. It uses both heat energy input and absorption to create the required pressure changes in the refrigerant. A suitable absorbent in the absorber first absorbs the refrigerant vapor, creating a solution. A little pump that uses very little mechanical energy is then used to raise the pressure of this solution (Herold et al., 2016; Wang & Oliveira, 2021). This system is especially useful where waste heat or low-grade thermal energy is available, making it energy efficient and environmentally friendly. This chapter presents the theoretical analysis of the system, including calculations for major components such as the evaporator, absorber, condenser, and pump, for a capacity of 1 ton of refrigeration (1 TR) (Khurmi & Gupta, 2013). It also describes the development and experimental operation of the system to validate its performance in achieving cooling, with minimal or no operating cost due to the utilization of waste heat as the energy source (Verma, P. (2023)).

Vapour Absorption Refrigeration System

VAR systems frequently employ refrigerant-absorbent mixtures (Zohar et al., 2007).
Compared to the compressor work in a VCR system, the pump requires far less work input since it processes liquid rather than vapor. In the generator, external heat energy is supplied through steam, hot water, gas burners, solar energy, or waste heat. Due to heating, the refrigerant separates from the absorbent solution in the form of high-pressure vapour, leaving behind a weak solution (Dincer & Kanoglu, 2010).

VAR SYSTEM FOR AUTOMOBILES

A significant amount of heat produced in an ICengine during combustion is not utilized for useful work and is instead rejected to the surroundings through exhaust gases and the engine cooling system. This rejected energy represents a valuable resource that can be effectively harnessed. In conventional automobiles, trucks, and buses, air-conditioning systems operate using mechanically driven compressors connected to the engine shaft (Manzela, A. A., Hanriot). In contrast, a VAR system can utilize waste heat from exhaust gases as well as heat dissipated by the engine cooling system. This otherwise unused thermal energy can be treated as a readily available energy source to drive the refrigeration cycle, thereby reducing dependence on mechanical power and improving overall system efficiency (Moran, M. J., Shapiro (2018)).

Therefore, integrating a VAR system in automobiles reduces the load on the engine by eliminating the need for a mechanically driven compressor. At the same time, it utilizes low-grade waste heat, such as exhaust energy, to produce the cooling effect. This approach enhances overall energy efficiency and contributes to reduced environmental impact by lowering fuel consumption compared to conventional VCR systems.

Methods of Implementation in Automobiles

In automotive applications of VAR systems, the required heat input can be provided through two primary sources:

1.Using heat from a separate fuel source: A VAR system can be operated using heat generated from a separate fuel, such as natural gas. In this approach, the fuel is burned in an independent combustion chamber, and the resulting heat is supplied to the generator to produce the required cooling effect. However, this method is generally not preferred, as it requires an additional fuel source and a separate combustion unit, making the system more complex, less economical, and relatively inefficient.

Using waste heat from an IC engine

An alternative and more efficient approach is to utilize the waste heat produced by an ICengine, which is otherwise performance, a VAR system can be operated efficiently. This method requires no additional fuel input, except for a small amount of electrical energy to run the pump, which can be supplied by the vehicle's battery. Therefore, it is highly suitable for automotive applications a key concern (Adewusi, S. A., & Zubair, S. M. (2022).

The heat generated from combustion increases the pressure of gases, causing the piston to move outward. This motion is transmitted to the crankshaft through the piston–crank mechanism, resulting in the production of mechanical work. However, only about 30% of the heat energy produced during lost to the surroundings in various forms. The residual heat energy is rejected to the surroundings through several pathways, including:

This portion of energy is referred to as low-grade energy, as it is available at relatively lower temperatures and is not directly useful for producing mechanical work.

Working of the system

In the pre-heater, its temperature is increased to nearly 75°C by utilizing engine cooling water available at approximately 80°C. This preheating step reduces the thermal load on the generator and enhances overall system efficiency. The heated solution then flows into the generator, where additional heat input causes the refrigerant component, typically water, to vaporize at around 40°C.

COMPARISON BETWEEN VAPOUR COMPRESSION AND VAR SYSTEMS

Advantages of VAR System over VCR System

Method of Refrigerant Compression

Refrigerant compression is a key step in any refrigeration cycle, as it influences all subsequent processes. In a VCR system, this function is performed by a mechanical compressor, which may be reciprocating, rotary, or centrifugal in design. In contrast, a VAR system eliminates the need for a mechanical compressor. Instead, the compression effect is achieved through a thermochemical vapour. This absorption converts the vapour into a liquid solution, significantly reducing its volume and effectively replacing the mechanical compression stage of the cycle.

MATHEMATICAL MODEL OF A VAR UNIT

VAR systems generally lower than that of vapour compression systems. For instance, a two-stage lithium bromide absorption system typically attains a COP of around 1.1. In comparison, vapour compression systems commonly used in air-conditioning applications can achieve COP values ranging from 4 to 5, indicating higher energy efficiency under similar operating conditions; instead, it can be supplied from various heat sources, provided they are at a sufficiently high temperature. In addition to improved energy utilization, these systems offer further advantages over vapour compression systems, such as significantly quieter operation.

As absorption systems gain wider application in both industrial and domestic sectors, their simulation and analysis become increasingly important for understanding their complex thermodynamic behaviour. Over the years, several mathematical models have been developed, with early studies primarily focusing on water–lithium bromide ($LiBr–H_2O$) working pairs. Further research has extended these analyses to multi-effect absorption systems.

Model implementation

The program generates numerical results for a single-effect absorption refrigeration system using either $LiBr–H_2O$ or $NH_3–H_2O$ as the working fluid pair.

Its basic form, the software enables users to specify operating conditions, based on which (COP) can be evaluated.
The results can also be easily visualized by the user using the built-in graphing tool.
Additional features of the program include:

The software provides the capability to plot thermodynamic refrigeration cycles on suitable property charts, allowing better visualization and analysis of system performance. It also offers access to thermodynamic property data for $LiBr–H_2O$ and $NH_3–H_2O$ working fluid pairs, Essential for accurate calculations and simulation of absorption refrigeration systems. In addition, the software includes a design tool that helps estimate the approximate size and specifications of major system components. These estimates are practical and useful during the preliminary design stage, enabling engineers and researchers to analyze, optimize, and develop efficient refrigeration system configurations effectively.

Model validation

The accuracy and reliability simulation model, the results were compared with a worked numerical example available in reference. The validation process involved matching the simulation outputs with the published data to evaluate the correctness of the developed model. By comparing important thermodynamic and performance parameters, the accuracy of the simulation was assessed. The selected problem included specific operating conditions and system requirements for the absorption refrigeration system. This comparison helped confirm that the simulation model could accurately predict system behaviour and performance under the given conditions, thereby validating its suitability for further analysis and study.

RESULTS

The produced simulation results can be compared with the system response under different operating situations. Along with the heat transfer rates in the generator and absorber under particular operating conditions, the coefficient of performance (COP) of a hypothetical system was also assessed. Understanding how system parameters can be changed to obtain optimal performance is improved by this analysis. $LiBr–H_2O$ and $H2O–NH_3$ systems were both thought to be running without condenser undercooling at an evaporator temperature of 5°C. The heat transfer rates were calculated per kW of refrigeration capability.
At a condenser temperature of 40°C, the contour lines shift toward lower COP values, indicating a reduction in system efficiency. Higher condenser temperature increases the condensing pressure and thermal load on the system, requiring more generator heat input. Consequently, the COP decreases as absorber temperature rises.

For the condenser temperature of 50°C, the reduction in COP becomes more significant, and a “non-operating” region appears at high absorber temperatures and low generator temperatures. In this region, the generator temperature is insufficient to drive refrigerant separation effectively, causing unstable system operation.

CONCLUSIONS

Developed in this study serves as an effective tool for the thermodynamic evaluation of VAR systems. Its user-friendly interface enables designers to estimate system performance under specified operating conditions with ease. Furthermore, the model supports detailed investigation of system behaviour by allowing variation of input parameters, making it valuable for both design applications and research studies.

In this work, simulations were carried out for both $LiBr–H_2O$ and $NH_3–H_2O$ working fluid pairs without incorporating a solution heat exchanger. The model has been validated using a standard numerical example and its results have been compared with those reported in existing literature. Future efforts will focus on validation using experimental data to further enhance reliability. The generalized mathematical framework also allows easy extension to more advanced configurations, such as multi-effect systems.

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