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Automotive exhaust gas flow control for an ammonia–water absorption refrigeration system

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HIGHLIGHTS

- An absorption refrigerator was driven by automotive exhaust gas heat.
- A system for controlling the refrigeration system heat input was developed.
- Excessive exhaust gas heat leads to ineffective operation of the refrigerator.
- Control of refrigerator's generator temperature led to better performance.
- The use of exhaust gas was possible for high engine speeds.

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ABSTRACT

A considerable part of the energy generated by an automotive internal combustion engine is wasted as heat in the exhaust system. This wasted heat could be recovered and applied to power auxiliary systems in a vehicle, contributing to its overall energy efficiency. In the present work, the experimental analysis of an absorption refrigeration system was performed. The exhaust system of an automotive internal combustion engine was connected to the generator element of an absorption refrigeration system. The performance of the absorption refrigerator was evaluated as a function of the supplied heat. The use of a control strategy for the engine exhaust gas mass flow rate was implemented to optimize the system. Exhaust gas flow was controlled by step-motor actuated valves commanded by a microcontroller in which a proportional-integral control scheme was implemented. Information such as engine torque, speed, key temperatures in the absorption cycle, as well as internal temperatures of the refrigerator was measured in a transient regime. The results indicated that the refrigeration system exhibited better performance when the amount of input heat is controlled based on the temperature of the absorption cycle generator. It was possible to conclude that, by dynamically controlling the amount of input heat, the utilisation range of the absorption refrigeration system powered by exhaust gas heat could be expanded in order to incorporate high engine speed operating conditions.

1. Introduction

The expansion of energy resources is one of the prime motivations for social and technological development. In the last decades, strong international concern has been raised with regard to the depletion of natural resources and an increase in pollution levels as a consequence of the higher energy consumption necessary to sustain productive activities. From an energy perspective, the use of internal combustion engines (ICEs) is of special interest, since these components account for up to 60% of the use of petroleum-derived fuels worldwide [1]. One of the key challenges to overcome in the development of ICEs, particularly those applied in automobiles, is the reduction of emissions (such as CO_2, CO, N_2O among other gases and particulates), which can be achieved by an increase in ICE efficiency [2], and the partial recovery of energy from the exhaust gases.

One of the characteristics of a conventional automotive ICE is that only approximately one third of the energy consumed during its use is actually converted into useful mechanical power. In water-cooled engines, the remaining two thirds of the total energy are wasted in engine cooling systems and exhaust gases, in similar proportions [3]. Automotive ICE performance is further impaired by the presence of auxiliary systems which draw from the mechanical work produced by the engine. Such is the case with conventional air conditioning systems used in cabin cooling or for transportation

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of goods which are based on vapour compression [4]. In this context, the development of on-board absorption refrigeration systems emerges as a possibility for increasing ICE efficiency in automotive applications. In contrast to vapour compression refrigeration systems, which require an active power source, absorption refrigeration cycles can be powered by the waste heat in the exhaust gases produced by an ICE [5,6].

The magnitude of the energy wasted in automotive ICE exhaust gas heat has been assessed by a number of authors [1,3,7–10]. Even though these studies generally agree that the amount of heat present in the exhaust gases could, in principle, be sufficient to power an on-board absorption refrigeration system, not enough power is considered to be available under idle or low engine throttle conditions. This was demonstrated in the work by Koehler and co-workers [8], who designed and tested a prototype for an absorption refrigeration system, powered by the exhaust gas heat of a 420 hp diesel engine. Performance of the system was evaluated by submitting the engine to work cycles representative of different traffic conditions (urban, mountainous roads and level roads). The authors showed that the amount of energy present in the exhaust gases was not sufficient to power a 5 kW absorption refrigeration system over approximately 20%, 40%, 80% of the running time for, respectively, level, mountainous, and urban traffic conditions. For this reason, it has been proposed that an on-board absorption refrigeration system powered by engine exhaust gas heat would be better suited for automobiles that are usually driven on highways, such as long distance coaches or trucks [11].

In spite of the difficulties related to the low energy available in exhaust gases for low engine throttle conditions, the utilization of exhaust gas heat in absorption refrigeration systems has been continuously pursued and, in some instances, viable models and prototypes have been achieved. For instance, Ramanathan and Gunasekaran [12] simulated an absorption refrigeration system powered by engine exhaust gases and indicated that for engine rotations as low as 1300 rpm, up to 2 kW power could be extracted from the engine exhaust. Talom and Beyene [4] showed that a 2.8 l V6 diesel engine could supply enough power to cool a 3-ton absorption chiller. The authors did point out, however, that further studies are required focussing on system reliability, regulatory issues regarding the use of ammonia or lithium bromide (common refrigerants used in absorption refrigeration systems), and the cost-benefit ratio of the added weight. The potential for utilizing the engine exhaust gases as a power source for absorption refrigeration in automobiles has also been confirmed by AlQdah [13]. The implementation of such systems, therefore, seems to be viable from a technical perspective as considered in a recent review [14], especially if we consider that mobile applications involving non-automotive engines have also been reported, e.g. in diesel operated locomotives [15–17] and boats [18,19].

Recently, Manzela and co-authors [20,21] evaluated the performance of a domestic absorption refrigerator modified for hot gas intake provided by a commercial 1.6 l four cylinder automotive engine. The impact of adapting the absorption chiller on engine performance, chemical composition of the exhaust gases, and fuel consumption was evaluated. The authors showed that, in spite of the low coefficient of performance (approximately 0.05), it was possible to reduce the average temperature in the refrigerator to close to 5 °C. Diverting exhaust gases to power an absorption refrigeration system does not cause a significant pressure drop in the exhaust flow, nor does it lead to an increase in the level of carbon emissions [20]. The authors also demonstrated that performance of the absorption refrigeration system powered by exhaust gas energy is hampered by excessive heat transfer to the absorption system, which occurs for higher engine speeds [8,20,21]. In this situation, exhaust gas temperature is increased considerably so that the refrigerant leaving the generator in the absorption cycle overheats and condensation is not achieved in the condenser. As a consequence, the evaporator temperature is raised and refrigeration does not occur. This highlights the importance of properly managing the amount of recovered heat in cogeneration systems based on ICEs [22].

In the present investigation, the performance of an absorption refrigeration system as a function of the ICE exhaust gas heat supplied was evaluated, in order to develop a control system which is capable of sustaining an optimal amount of heat input. To this end, the exhaust system of an automotive ICE was connected to the generator element of a commercial ammonia–water absorption refrigerator originally designed to operate with the heat produced by an LPG burner. Some advantages of utilising ammonia–water as a working pair for a practical heat recovery application have been highlighted by Han and co-workers [23]: ammonia is naturally available, environmentally benign, inexpensive and extensively used in industry. Exhaust gas flow was regulated by a set of step-motor driven control valves, developed specifically for the present study. The generator temperature was chosen to be the control system reference variable since it is directly influenced by the

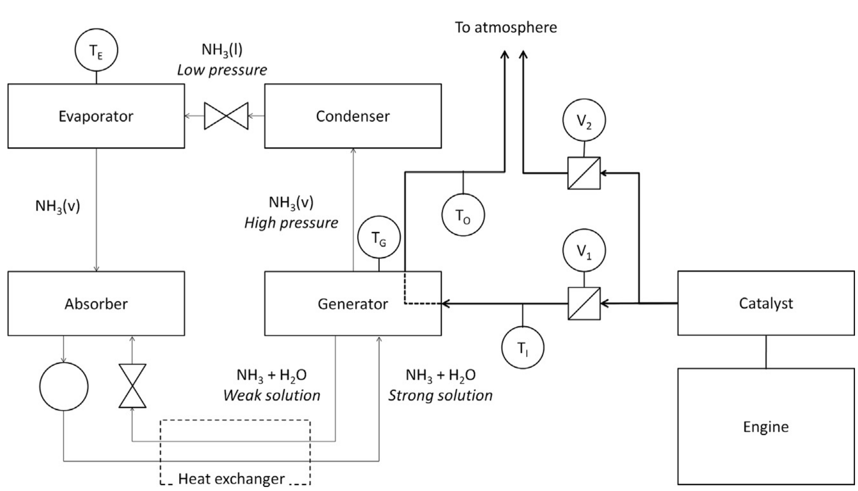

Fig. 1. Basic layout of the experimental setup showing the absorption cycle and the circuit used to transfer heat from the engine exhaust to the generator element of the refrigeration system.