



13th IEA Heat Pump Conference
April 26-29, 2021 Jeju, Korea

Dynamic simulations of an absorption refrigeration system for automobile application

Hai Trieu Phan^{a,*}, Mathilde Wirtz^a, Julien Hergott^b and François Boudehenn^a

^aUniv. Grenoble Alpes, CEA, LITEN, DTBH, 38000 Grenoble, France

^bFaurecia Clean Mobility, R&D Center, 25550 Bavans, France

Abstract

This study was aimed at evaluating the technological feasibility of an absorption refrigeration system using heat from the exhaust gases to cover the needs of air conditioning in automobiles. In the first step, architecture of a single-stage ammonia-water absorption cycle was designed for a case study with a standard 2.0L gasoline turbo-engine vehicle. Then, a new dynamic model of the absorption cycle was built based on the TIL Modelica library to simulate the transient behaviour of the cycle during start/stop and change in driving regime. The simulation results show two major limitations of the absorption refrigeration: insufficient cold production for low wheel power (urban cycle); and slow start up compared to a conventional compression system. The dynamic of the absorption cycle is slow enough to make the engine speed fluctuations (including the stop & start function) imperceptible by the users. Analysis of the ammonia mass flow rate in the system exhibits that the inertia of the absorption cycle mainly depends on high-pressure components such as generator and condenser. This study provides some insight to optimize the performance and the dynamic of the absorption refrigeration system for automobile application.

Keywords: absorption refrigeration; dynamic simulation; heat recovery

1. Introduction

Today, compression refrigeration system (CRS) is the most used refrigeration system in automobiles, requiring approximately 8% to 12% of the engine rated power for air-conditioning. As a result, the average fuel oil consumption increases approximately 16% to 20% when driving automobile with air-conditioning in operation [1]. As automobiles have 35% to 40% thermal efficiency rate, the remaining primary energy is consumed for cooling liquid/lubricant, and in exhaust gases [2]. Nowadays, studies focus on the improvement of thermal efficiency by achieving a better fuel consumption. While utilization of the heat dissipated in exhaust gases for turbo charging and cabin heating has been browsed, more and more studies [3 – 4] focus on air-conditioning by waste heat refrigeration system (WHRS). However, WHRS is a crucial topic still not at a maturity state, because of specific technical requirements. WHRS should be compact and light to fit the narrow space of automobiles. They need to be cooled by air directly and must operate whenever the vehicle runs, under any road/driving conditions. Furthermore, the working fluids should be low toxic, low flammable, able to work under the operating pressure and provide good heat and mass transfers [3]. Ammonia-water absorption refrigeration system (ARS) is a promising solution, with the ammonia filling all the working fluids constraints.

Horuz [5] experimentally proved the possibility of using absorption refrigeration system (ARS), feed by the waste heat in exhaust gases from a 6L diesel vehicle. The prototype is a 10kW commercial single-stage NH₃-H₂O system. The author shows ARS can replace both the internal combustion (IC) system and the compressor of the CRS. Kaewpradub & al. [6] investigate a single-stage LiBr-H₂O absorption refrigeration system. Experiments are led at different engine speeds, expansion valve openings, condenser-outlet temperatures and solution flow rates. The coefficient of performance (COP = Cold produced power/Sum of thermal and electricity input powers) and cooling load increase with the engine speed, and the drop of condenser outlet temperature. The cooling load and COP reach maximal values of 700W and 0.28 respectively, at 1400 rpm and 25°C at condenser outlet. When the solution mass flow rate increases, the cooling load capacity increases

* Corresponding author. Tel.: +33 4 79 79 23 72; fax: +33 4 38 78 53 96.

E-mail address: haitrieu.phan@cea.fr.

too, but the COP drops. Koehler & al. [7] developed a detailed model and designed a breadboard prototype of a single-stage NH₃-H₂O absorption system for truck refrigeration. The heat is provided from the exhaust-gases, at a temperature of around 460°C and a mass flow rate of 360 kg/h. The evaporation temperature varies between -20°C and 0°C, while ambient temperature is from 20°C to 30°C. The prototype COP is from 0.23 to 0.30 with a cooling capacity of 6-10kW.

Charate & al. [4] provide a literature review on air-conditioning in a car, using absorption refrigeration supplied by exhaust heat. Chandrakar & al. [8] designed a NH₃-H₂O absorption refrigeration system for a 4-cylinder car. Evaporator can produce 2.6 kW of cold, from 4.5 kW of heat; with a COP of 0.57. Rixon & al. [9] designed and built a NH₃-H₂O absorption refrigeration system from pieces recovery. COP reaches 0.14, with exhaust gases temperature between 100°C and 180°C. Vicatos & al. [10] conducted a theoretical analysis, and developed a unit tested in a laboratory and on road. COP reaches only 0.09. Talom & Beyene [11] led an experimental study on a 10.6 kW absorption chiller, modified to be supplied by a 2.8L V6 IC engine. Results show the concept feasibility and the increase of the system performances.

Most of the authors [5, 4; 8-10] highlight that the use of exhaust gases for air-conditioning allow to reduce IC, fuel consumption, noise and atmospheric pollution, while maintaining efficiency of the engine. However, in most of the studies, the COP is low, about 0.1 to 0.3, which means that further researches for cycle improvement are necessary. According to [5], some points need to be strengthened: pressure variations, and fluctuations of cooling capacity regarding the vehicle speed. An important issue, underlined by [5, 7, 8], is when the vehicle is parked or move slowly: ARS is not sufficient, an alternative solution or a complementary heater is needed. In [7], the authors insist that this system is promising for long distance driving, but is not robust when exhaust gases are low. In [4; 8-10], the authors show that NH₃/H₂O is the best working fluid couple compromise, being environment friendly and efficient enough.

Xu & al. [3] propose an interesting alternative solution for stationary problem: a novel absorption-compression hybrid refrigeration cycle (ACHRC) driven by gases and power from vehicle engines. R124-DMAC mixture is used as a working fluid. The ARS is powered by exhaust gases; and the CRS, driven by power, runs only if ARS cannot supply enough cooling capacity. For ambient and evaporator temperatures of 35°C and 3°C respectively, the maximum air-conditioning power is 30 kW, while rated generator load in the ARS is 58.68 kW. When the waste heat load recovered by the generator reaches its rated value, air-conditioning is fully supplied by ARS and the maximum integration COP is 0.5. Otherwise, CRS operates to cover the lack of cooling capacity and the COP is reduced. Ambient temperature greatly affects the operating characteristic of the ACHRC: when it rises, the maximum value of the integration COP reduces significantly.

The previous studies focus on the feasibility of ARS process for automobile applications. This process has been proved efficient for monotonic driving at a cruise speed, but an important lock remains to be lifted: the good operation of the ARS during stationary immobile period, start/stop and fluctuations of the vehicle speed. Most of the studies about ARS system for automobile do not consider the dynamic performance of the chiller, which is yet significant for the whole system performances. Indeed, stabilization is deeply affected by transient processes [14]. Even though they are not focus on automobile applications, some studies about dynamic modelling of absorption chiller have been led so far.

Kim and Park [12] and Cai & al. [13] presented dynamic simulations of single-effect NH₃-H₂O absorption refrigeration system. The numerical model of [12] was applied to a 10.5 kW commercial chiller, to observe the behaviour of several parameters during start-up operation, and find the best conditions for the shortest time constant, with optimal cooling production. A low mass of solution in a large generator volume, combined with a stepwise turn-up/turn-down flue of gas flow rate seems to be the ideal solution for start-up operation. In [13], the authors studied the dynamical response to a pressure step change, and showed that mass flow and heat rates as well as COP oscillated during approximately two loops circulation times before reaching a steady state. Wang & al. [14] analysed the performances of a dynamic model of a single-effect H₂O-LiBr absorption chiller, under different parameters. The time required to reach steady-state increases when generator inlet temperature widely change, when cooling water inlet temperature rises, and when evaporator inlet temperature drops. Viswanathan & al. [15] developed a model able to simulate the transient behaviour of an absorption chiller, exploring the entire start-up and shutdown processes for step change of several parameters. Flow rates, pressures and concentrations were stable after 3 minutes. Evaporator and condenser took longer times to reach steady state conditions.

As a continuous of the literature studies, this work aims at bringing further investigation to evaluate the performance of an absorption refrigeration in automobile. A new dynamic model of an absorption cycle feed by exhaust gases was developed to simulate the transient behaviour of the cycle during start/stop and change in driving regime. The simulation results gave the dynamic profiles of hydrodynamic and thermal parameters in different component as well as the system characteristic times. Analysis of the refrigerant mass flow enabled us to identify the key processes and components affecting the dynamic of absorption refrigeration system. Based on this, some ideas are suggested in order to improve the system performance and inertia.

2. Case study and architecture

The present study focuses on evaluating the feasibility in term of the dynamic performance of an absorption refrigeration in order to respond to a given cold request. The other constraints related to the integration of the machine into the vehicle such as vibration, acceleration, deceleration, geometrical layout, weight, fluid charge, etc. are not considered. The case study is a standard 2.0 L gasoline turbo-engine vehicle, which requires a maximum cold production of 5 kW at 5°C of air temperature in the passenger compartment. The driving cycle presented in Fig. 1 corresponds to FTP-75 cycle [16], which has been used for emission certification and fuel consumption testing of light duty vehicles in the United States. This cycle is interesting for this study because of level of acceleration and number of start/stop phase. The first step of thermal system design suited for transient heat sources is to select the power design point, which is important to size all the components, especially heat exchangers. To support design point selection, we have developed a methodology based on analysis of exhaust energy distribution on the cycle. Main output of this methodology are the time fraction, exhaust energy fraction, and average values of parameters such as exhaust temperature and mass flow, on given exhaust power range, as shown in Table 1. It is observed that the available power of the exhaust gases strongly depends on the exhaust-gas flow rate, which depends directly on the engine power. During 62% of time, the vehicle stops or runs at low speed (Point 0 and Point 1), giving low exhaust-gas power.

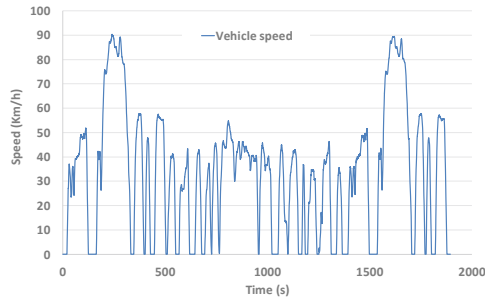


Fig. 1. Typical profile of the vehicle speed

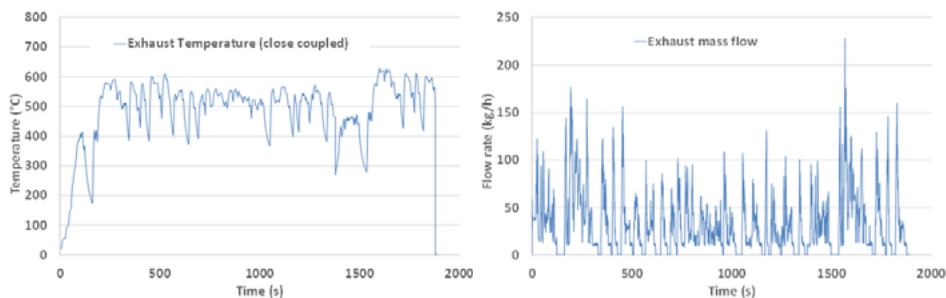


Fig. 2. Evolution of the temperature and flow rate of the exhaust gases

Table 1. Time fractions and average parameters of different range of exhaust power. T_{air} is the ambient temperature.

Point	Range of Available Exhaust Power with $T_{air} = 20\text{ }^{\circ}\text{C}$ [kW]	Time fraction	Exhaust Energy Fraction	Average of Vehicle speed [km/h]	Average of Exhaust mass flow [kg/h]	Average of Exhaust Temperature [$^{\circ}\text{C}$]	Average of Available Exhaust Power with $T_{air} = 20\text{ }^{\circ}\text{C}$ [kW]
0	= 0	17,41%	0,00%	0,0	0,0	385,4	0,0
1	]0-5]	44,49%	21,24%	32,9	19,1	468,9	2,4
2	]5-10]	23,19%	32,73%	46,4	44,3	534,3	7,1
3	]10-15]	8,17%	19,87%	48,4	73,6	551,1	12,2
4	]15-20]	4,09%	13,96%	56,0	100,2	564,0	17,1
5	]20-25]	2,10%	9,21%	60,6	128,0	567,2	22,0
6	]25-30]	0,49%	2,65%	56,5	156,7	566,6	27,0
7	]30-35]	0,04%	0,24%	50,6	202,1	526,6	32,2
8	]35-40]	0,02%	0,11%	50,0	224,8	525,8	35,8

Fig. 3 shows the architecture of the absorption refrigeration of this study. It contains a generator, directly heated by the exhaust gases; an absorber, a rectifier and a condenser, which evacuate heat to the ambience; an evaporator directly produces cold air; a solution heat exchanger (also called economiser); two expansions valve (one for the refrigerant and one for the weak solution) and a solution pump. The system also includes several tanks: T2 and T3 for liquid-vapour separation, T1 for solution storage and T4 for refrigerant storage. Using a standard air heat exchanger with a difference temperature between the air and the fluid of around 10K. The production of cold air at 5°C requires a negative evaporation temperature of the refrigerant. That is the reason why we investigated the absorption refrigeration using the couple $\text{NH}_3/\text{H}_2\text{O}$ as working fluids.

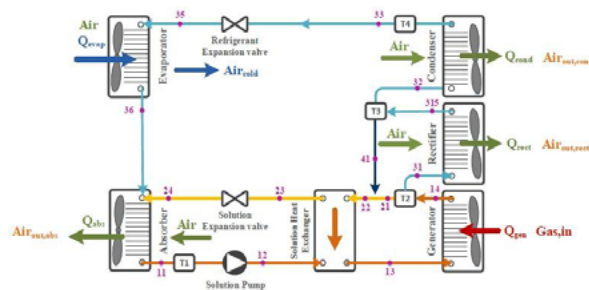


Fig. 3. Schematic view of the architecture of the absorption-refrigeration system

3. Dynamic model

A dynamic model of the above architecture was developed based on Modelica language using the commercial TIL library of TLK-Thermo GmbH, which contains a number of pre-set components and fluid property (based on REFPROP). The component diagram of this model is shown in Fig. 4.

We considered the following hypothesis in different components:

- Heat exchangers:
 - ✓ Air heat exchangers (generator, absorber, rectifier, condenser and evaporator) are fin-and-tube type with tube wall in stainless steel and fins in aluminium;
 - ✓ Liquid-liquid heat exchanger (economiser) is plate type with wall in stainless steel;
 - ✓ The heat exchange coefficients in the exchangers are imposed. On the gas side, the heat exchange coefficient is in the order of magnitude of $100\text{ W/m}^2/\text{K}$ on design point. On the liquid side, the heat exchange coefficient is in the order of magnitude of $1000\text{ W/m}^2/\text{K}$. On the two-phase side, the heat exchange coefficient is in the range of $2000\text{--}4000\text{ W/m}^2/\text{K}$;
 - ✓ The geometries of the heat exchangers were previously determined by static calculations to target heat exchanger efficiencies around 0.85 at Point 2 (see Table 1);
 - ✓ The pressure drops are not calculated;
- Expansion valves: a linear relationship between the pressure drop and the mass flow rate is used: $\dot{m} = \text{open} \times \Delta P$, open is the effective valve opening;

- Tanks: only tanks T2 and T3 where there are separation of liquid and vapour phases are simulated. An artificial pump is used to impose a stable liquid level in tank T3 as observed experimentally with the absorption-chiller prototypes in our laboratory. In reality, the liquid in tank T3 returns to the poor solution due to gravity;
- Air flow: the inlet temperature of air is fixed at 30°C. The air-flow rates were previously determined by static calculations to target a variation in temperature of about 15°C from inlet to outlet for absorber, condenser and rectifier;
- Regulation parameters: pump flow rate and expansion-valve openings;
- Initial conditions: the initial conditions of dynamic simulations are set as below:
 - ✓ Pressures : 10 bar (based on experimental data);
 - ✓ Wall temperatures : 30 °C (equal to the ambient temperature);
 - ✓ NH₃ mass fractions in different components given by static simulations.

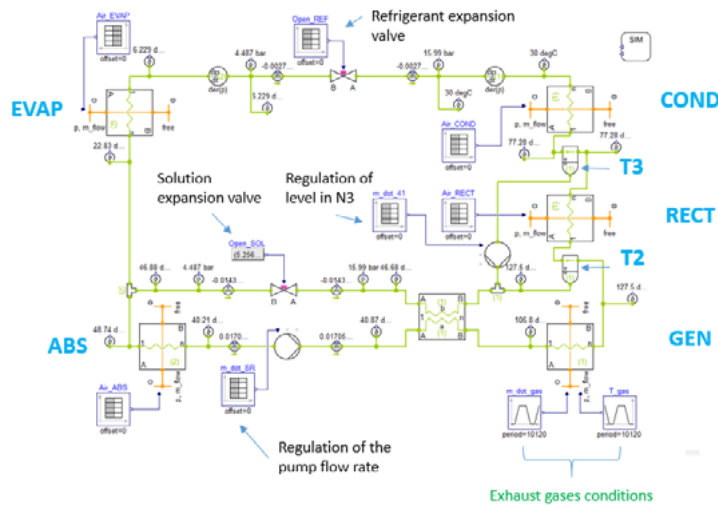


Fig. 4. Component diagram of the dynamic model of the absorption-refrigeration system

4. Simulation results

4.1. Constant pump flow rate and valve openings

For this case, we set the pump flow rate to the average value given by static simulations (45 kg/h) and fixed the valve openings to obtain the target difference of the pressures in the system. We performed simulations with the exhaust inputs as shown in Fig. 2 and obtained the evolutions of the power in different components: evaporator, condenser, absorber and generator. As shown in Fig. 5, the power at the generator fluctuates significantly due to fluctuations in the exhaust conditions. Since the condenser and the generator are connected at the same pressure level (high pressure), they show similar dynamic behaviour. At the low-pressure side, the absorber and the evaporator show smoother curves. After 250 s (~ 4 minutes), we observe a sudden increase of the cold power to 80% of the stabilized value, mainly due to the highly increase of the generator power. The cold production is maintained even when the vehicle stops. The system dynamic is slow enough to make imperceptible by the customer the fluctuations in engine speed/load. The stabilized cold power is around 2.3 kW, significantly lower than the maximum power required of 5 kW.

For a better understanding of the main factors affecting the system dynamic, we analyse the evolution of the pressure and the ammonia flow rates in different components. As shown in Fig. 6a and Fig. 6b, there is high peak of ammonia-vapour production at the generator outlet between 200s and 250s, leading to a sudden increase of the high pressure. At 250s, the high pressure approaches 15 bar, generating condensation inside the condenser. Then, the liquid flow rate remains stable at the condenser outlet due to hydrodynamic constraint.

The rest of the produced ammonia liquid is accumulated in the condenser (see Fig. 6c). In reality, this amount of ammonia liquid is stored in tank N4 (see Fig. 3) to do not degrade the condenser performance. Passing through the expansion valve, the ammonia liquid enters the evaporator at nearly saturated condition and therefore it is rapidly evaporates. That is the reason why only a small amount of ammonia-liquid presents in the evaporator.

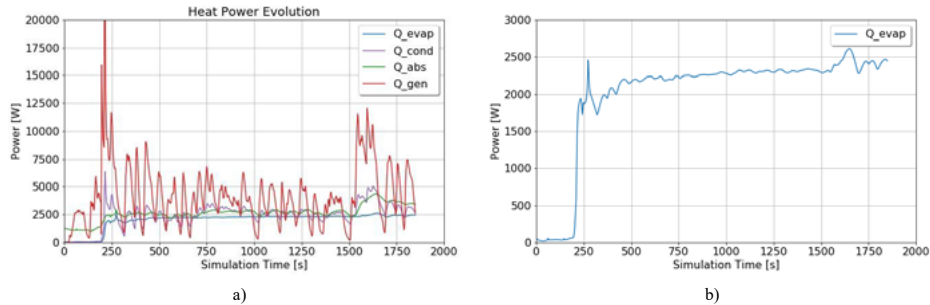


Fig. 5. Evolutions of power: a) Q_{evap} at evaporator, Q_{cond} at condenser, Q_{abs} at absorber and Q_{gen} at generator; b) a zoom on power at evaporator

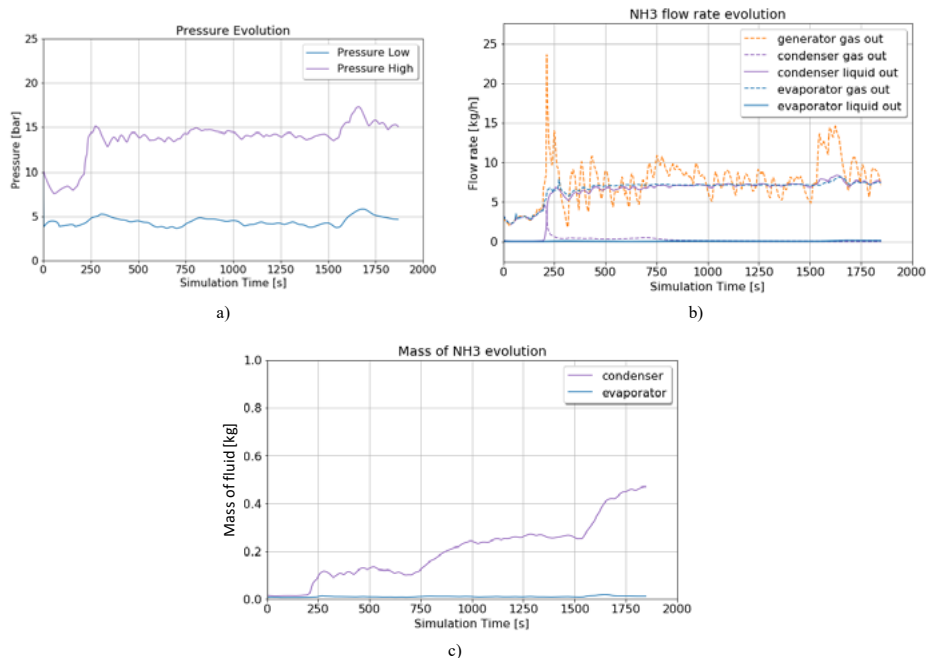


Fig. 6. Evolution of a) pressures; b) ammonia flow rates and c) ammonia mass in the heat exchangers

The above analysis shows that the absorption refrigeration dynamic strongly depends on hydrodynamic in the system. Different from a mechanical-compression machine, during the starting phase, the pressure in an absorption chiller increases by ammonia-vapour production from the generator. The starting time corresponds to the time required for the high pressure to reach the saturation value so that condensation occurs in the condenser. Once ammonia liquid is generated, cold power can be rapidly produced since the ammonia liquid enters the evaporator at nearly saturated condition.

4.2. Regulated pump flow rate and valve openings

To investigate the impact of the regulation parameters, we perform simulations with the following conditions for pump flow rate and valve openings:

- The pump flow rate is regulated to maintain a constant temperature of the weak solution at the generator outlet with the following laws (as illustrated in Fig. 7):
 - Start ($t < 250$ s) : $\dot{m}_{pump} = \dot{m}_{pump, mean} = 45$ kg/h
 - After start ($t \geq 250$ s) :
 - ✓ $\dot{m}_{pump} = \frac{\dot{m}_{pump, mean}}{\dot{m}_{gas, mean}} \dot{m}_{gas} = 1.4 \times \dot{m}_{gas}$ if $\dot{m}_{gas} > \frac{\dot{m}_{gas, mean}}{2} = 16.2$ kg/h
 - ✓ $\dot{m}_{pump} = \frac{\dot{m}_{pump, mean}}{2} = 22.5$ kg/h if $\dot{m}_{gas} \leq \frac{\dot{m}_{gas, mean}}{2}$
- The valve openings are regulated to maintain a constant difference between high and low pressures :
 - Refrigerant valve : $Open_{ref} = k1 \times \dot{m}_{pump, mean}$ with $k1 = 160 \times 10^{-9}$ [1/Pa]
 - Solution valve : $Open_{sol} = k2 \times Open_{ref}$ with $k2 = 5.26$

Fig. 8 shows comparison of cold production with constant and variable pump flow rates. After the start-up, the cold production reacts rapidly with the change in pump flow rate. Because the regulation of the valves is fast enough (~ 1 s) to adjust the pressure levels in the system so that condensation and evaporation of the refrigerant occur continuously. At high exhaust gas power, an increase in the pump flow rate will lead to an increase in the refrigerant flow rate and thus improve the cold production. For future works, better regulation laws can be developed to optimize the machine performance.

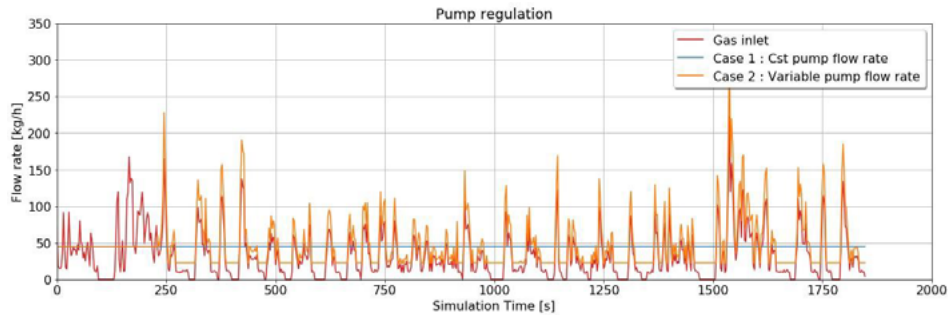


Fig. 7. Pump regulation with case 1: constant flow rate and case 2: variable flow rate

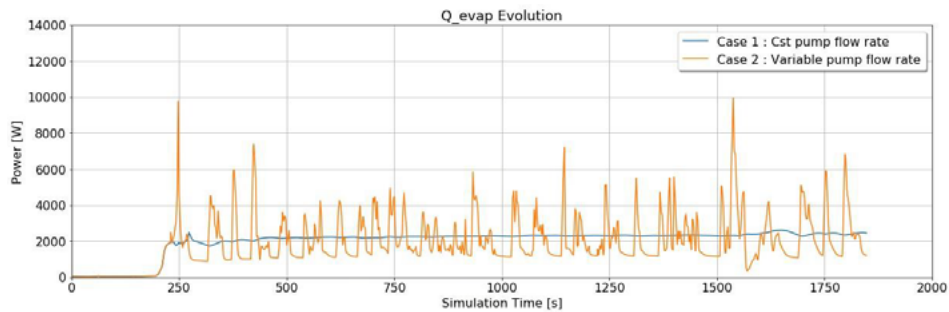


Fig. 8. Cold power productions with constant and variable pump flow rates

5. Conclusions

This study investigates the dynamic performance of an absorption refrigeration heated by exhaust gases. The case study is a standard 2.0L gasoline turbo-engine vehicle running on FTP-75 driving cycle. In agreement

with the literature, dynamic simulations confirm insufficient cold production when the vehicle runs at low engine power (low speed and/or low torque). Another technological limitation is the high inertia of the system that causes long start-up time, around 4 minutes in the present case study. The key factor affecting the absorption refrigeration dynamic is the high-pressure level, which mainly depends on the vapour generation at the generator. For the system to start, the high pressure should reach the necessary value allowing condensation in the condenser. Boosting the generator power (for example by adding complementary heat) for fast vapour production could be a solution to reduce the start-up time. After the start-up, the cold production reacts rapidly with the regulations of pump flow rate and valve openings. Smart regulation law could be a solution to improve the machine performance.

Acknowledgements

The French Alternative Energies and Atomic Energy Commission (CEA) and FAURECIA Clean Mobility for their supports to this work.

References

- [1] Fang, GY, Li, H, Automotive air conditioning technology. *China Machine Press*: Beijing, 2002
- [2] Horuz, I, Vapor absorption refrigeration in road transport vehicles. *Journal of Energy Engineering* 1999;**125**:48-58.
- [3] Xu, S, Li, J, Liu, F. An investigation on the absorption–compression hybrid refrigeration cycle driven by gases and power from vehicle engines. *International journal of energy research*, 2012
- [4] Charate, T, Awate, N, Padir, S, Dubey, D, Kadam A. A review of Absorption refrigeration in vehicles using waste exhaust heat. *International Journal of scientific & engineering research*, volume 8, March 2017
- [5] Horuz, I. An Alternative Road Transport Refrigeration. *Journal of engineering and environmental science* 1998
- [6] Kaewpradub, S, Sanguanduean, P, Katesuwan, W, Chimres, N, Punyasukhananda, P, Asirvatham, LG, Mahian, O, Dalkilic, AS, Wongwises, S. Absorption refrigeration system using engine exhaust gas as an energy source. *Case studies in thermal engineering*, 2018;**12**:797-804
- [7] Koehler, J, Tegethoff, WJ, Westphalen, D, Sonnekalb, M. Absorption refrigeration system for mobile applications utilizing exhaust gases. *Heat and Mass Transfer*, 1997;**32**:333–340.
- [8] Chandrakar, D, Saikhedkar, NK. Design of ammonia water vapor absorption air conditioning system for a car by waste heat recovery from engine exhaust gas – *Advance physics letter*, volume 3, 2016, ISSN:2349-1108
- [9] Rixon, KL, Sanoj, T, Mathew, C, Thomas, T. Air cooling inside vehicles using vapor absorption refrigeration system. *International journal of engineering research & technology*, volume 4, 2015. ISSN:2278-0181
- [10] Vicatos, G, Gryzagoridis, J, Wang, S. A car air-conditioning system based on an absorption refrigeration cycle using energy from exhaust gas of an internal combustion engine. *Journal of energy in southern Africa* 19, 2008
- [11] Talom, H, Beyene, A. Heat recovery from automotive engine. *Applied thermal engineering* 2009;**29**:439-444
- [12] Kim, B, Park, J. Dynamic simulation of a single-effect ammonia-water absorption chiller. *International journal of refrigeration*, 2007;**30**:535-545
- [13] Cai, W, Sen, M, Paolucci, S. Dynamic simulation of an ammonia-water absorption refrigeration system. *Industrial & engineering chemistry research*, 2012;**51**:2070-2076
- [14] Wang, J, Shang, S, Li, X, Wang, B, Wu, W, Shi, W. Dynamic performance analysis for an absorption chiller under different working conditions. *Applied sciences*, 2017;**7**:797
- [15] Viswanathan, V, Rattner, A, Determan, M, Garimella, S. Dynamic model for small-capacity ammonia-water absorption chiller. *International refrigeration and air conditioning conference*, 2012
- [16] DieselNet, Emission Test Cycles, FTP-75, <https://www.dieselnet.com/standards/cycles/ftp75.php>