Purdue University
Purdue e-Pubs

International Refrigeration and Air Conditioning Conference

School of Mechanical Engineering

2010

An Adsorption Air-Conditioning System to Reduce Engine Emissions and Fuel Consumption for Heavy-Duty Vehicles

Yongfang Zhong
Penn State Erie

Kevin L. Wert
Thermacore Inc.

Tiegang Fang
North Carolina State University

An Adsorption Air-Conditioning System to Reduce Engine Emissions and Fuel Consumption for Heavy-Duty Vehicles

Yongfang ZHONG[1]*, Kevin L. WERT[2], Tiegang FANG[3]

[1]School of Engineering, Pennsylvania State University,
Erie, Pennsylvania, USA
814-898-6798, yxz27@psu.edu

[2]Thermacore Inc.
Lancaster, Pennsylvania, USA
717-519-3140, k.l.wert@thermacore.com

[3]Mechanical and Aerospace Engineering Department, North Carolina State University,
Raleigh, North Carolina, USA
919-515-5230, tfang2@ncsu.edu

* Corresponding Author

ABSTRACT

An adsorption air conditioning system is proposed to provide cooling for heavy-duty vehicles. This system is powered by waste heat when the engine is running. When the engine is off, it can be operated by fuel fire heaters, a recently implemented technology to reduce the idling of heavy-duty vehicles. Hence, this system can not only reduce engine emissions but improve the overall engine efficiency. A model of the adsorption system using the zeolite-water working pair is developed and the system performance with different operating cycle is reported. The results show that the COP of the system increases with the length of the cycle period but the total cooling capacity decreases during the same period of operation. The dynamic performance of the system provides guidance for the system control and energy minimization.

1. INTRODUCTION

Heavy-duty vehicles, including on-highway, off-highway, bus and rail, consume more than 25% of the fuel used in the transportation sector and have a national impact on air pollution and greenhouse gas production (Davis *et al.* 2008). Generally, the efficiency of a diesel engine is approximately 40% and the rest of the energy is rejected as waste heat to the coolant and the exhaust gas (Agnew *et al.* 1999; Zhang 2000; Talbi *et al.* 2002; Giannelli *et al.* 2004). Simultaneously, heavy-duty vehicles have considerable cooling requirement in the cab and the sleeper. For instance, more than 800 million gallons of fuel are used annually to idle the engine for long-haul trucks, primarily to condition the cab and the sleeper (Gaines *et al.* 2006). Idling heavy vehicles also produces airborne emissions and noise. A number of cities and states such as Philadelphia PA and California have banned or restricted vehicle idling. Therefore, an environment-friendly cooling technology is needed to reduce emissions and to improve the energy efficiency of heavy-duty vehicles.

Heat powered adsorption air-conditioning system is a promising method to improve the energy efficiency and reduce air pollution. Zhang (2000) experimentally demonstrated the feasibility of using an adsorption cooling system driven by waste heat from a small diesel engine of 40 horsepower (30kW). Lambert and Jones (2006a) compared adsorption (solid-vapor), absorption (liquid-vapor), Stirling and Peltier coolers, and concluded that adsorption heat pump is the most practical technology for automobiles. They (2006b) also reported detailed design and analysis of critical components of the system. Wang and Oliveira (2006) reviewed various applications and current development of adsorption system. In this work, an adsorption air conditioner is studied for heavy-duty vehicles. System operation is described and a model of the system using zeolite as the sorbent and water as the refrigerant is developed to evaluate the transient performance in order to guide the control of the system.

2. SYSTEM OPERATION

The schematic of the adsorption system proposed for heavy-duty vehicles is shown in Figure 1. When Adsorber 1 is connected to the evaporator and Adsorber 2 is connected to the condenser, the sorbent in Adsorber 1 is cooled by the fluid from heat sink and adsorbs the refrigerant from the evaporator, providing cooling for the vehicle. Simultaneously Adsorber 2 is heated by the fluid from the heat source and the refrigerant is desorbed from the sorbent, condenses in the condenser and then flows to the evaporator through the expansion device. The process in Adsorber 1 is called adsorption and the one in Adsorber 2 is desorption. In order to provide continuous cooling, Adsorber 1 and Adsorber 2 switch their functions between adsorption and desorption after a certain cycle period of operation. The refrigerant flow between the adsorbers and the heat exchangers is controlled by the valves. The evaporator is always connected to the adsorber in the adsorption phase, and the condenser is connected to the adsorber in the desorption process. The heating and cooling of the adsorbers are managed by the fluid control unit.

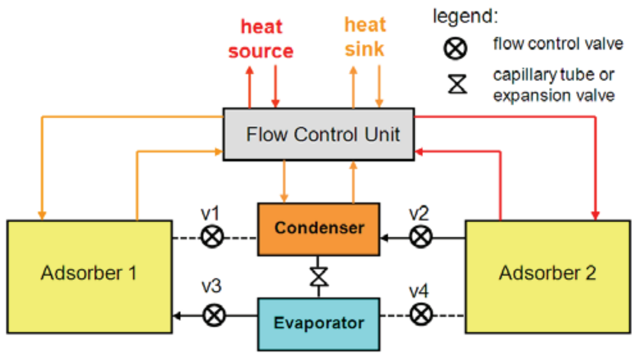


Figure 1 Adsorption cycle (solid lines with arrows illustrate flow direction and the dashed lines indicate that the valves in the line are closed and no fluid flows in the passages between the adsorber and the heat exchanger.)

The adsorption air-conditioning system can exploit the engine waste heat when the vehicle is running. The waste heat can come from two sources in the diesel engines of heavy-duty vehicles. One source is the exhaust gas from the tailpipe, and the other is the EGR cooler. The exhaust gas from the tailpipe in heavy-duty vehicles is typically in the temperature range from 150°C to 450°C (Ainslie et al. 1999). The coolant temperatures out of EGR coolers are above 100°C (Agnew et al. 1999; Talbi et al. 2002; Stolz et al. 2001; Hendricks et al. 2002; Herner et al. 2009). When the engine is off, the fuel fire heater can be used to drive the adsorption system. The fuel fire heater is an idle-reduction technology applied to heavy-duty vehicles to provide heating when engine is off. It produces low emissions and significantly reduces air pollution. This technology can be used for cooling purpose when an adsorption air-conditioner is applied to heavy-duty vehicles.

3. MODEL DESCRIPTION

The performance of an adsorption system is dominated by the mass, momentum and energy transport processes in the adsorbers. Assuming that the two adsorbers shown in Figure 1 operate independently of one another, the model focuses on the performance of a single adsorber, including its interactions with the fluid control unit, its connected heat exchanger (either evaporator in the adsorption phase or condenser in the desorption process). The adsorber is treated as having spatially uniform but time varying properties (transient lumped parameter analysis). Water is used as the refrigerant and zeolite as sorbent in the system. Mass conservation of the adsorber is given by:

$$\frac{dm_{vapor}}{dt} + m_s \frac{dY_{sorb}}{dt} = \dot{m}_{evap} - \dot{m}_{cond} \tag{1}$$

where Y_{sorb} is the concentration of the adsorbed water in the dry sorbent m_s, i.e. the ratio of the adsorbed water to dry sorbent; m_{vapor} is the mass of water vapor in the adsorber; $\dot{m}_{evap}$ and $\dot{m}_{cond}$ are the water from the evaporator and to the condenser, respectively. In the model, this water flow is represented by a pair of conditional relationships:

$$\dot{m}_{evap} = \begin{cases} (P_{evap} - P_{sorb})/R_{flow}, & \text{if } P_{evap} > P_{sorb}, \text{adsorption} \\ 0, & \text{if } P_{evap} \le P_{sorb}, \text{desorption} \end{cases} \quad (2)$$

$$\dot{m}_{cond} = \begin{cases} (P_{sorb} - P_{cond})/R_{flow}, & \text{if } P_{sorb} > P_{cond}, \text{desorption} \\ 0, & \text{if } P_{sorb} \le P_{cond}, \text{adsorption} \end{cases} \quad (3)$$

R_{flow} is the flow resistance. Mass transport between the adsorber, evaporator and condenser is controlled by a pair of valves, each of which allows flow only in one direction (Figure 1). When a valve is "open" the mass flow rate is linearly proportional to differential pressure via R_{flow}.

Mass transport within the sorbent is simulated via a linear driving force (LDF) model (Gorbach *et al.* 2004). The rate of change in the adsorbed water is linearly proportional to the difference between the current value (Y_{sorb}) and the thermodynamic equilibrium value ($Y_{sorb,eq}$). $Y_{sorb,eq}$ is a function of water vapor pressure and sorbent (zeolite) temperature in the adsorber. The factor K_{LDF} is the mass transfer resistance and proportional to the mass diffusivity. Hence,

$$\frac{dY}{dt} = K_{LDF}(Y_{sorb,eq} - Y_{sorb}) \quad (4)$$

Energy conservation of the adsorber is given by:

$$(m_{vapor}C_{v,vapor} + m_s Y_{sorb} C_{v,liquid} + m_s C_{v,s}) \frac{dT_s}{dt} = \dot{Q}_{adsorber} + m_s \beta h_{fg} \frac{dY_{sorb}}{dt} - P_s(v_{vapor} - v_{liquid}) m_s \frac{dY_{sorb}}{dt} + v_{vapor}\left(T_s \frac{\partial P}{\partial T}\bigg|_v - P_s\right)\frac{dm_{vapor}}{dt} + (u_{vapor} - h_{vapor})\dot{m}_{cond} - (u_{vapor} - h_{evap})\dot{m}_{evap} \quad (5)$$

$$\dot{Q}_{adsorber} = UA_{sorb}[T_{FCU}(t) - T_s] \quad (6)$$

The left side of the equation is the energy change in the adsorber. The first term of the right side is the heat exchanged with the fluid flow by the flow control unit, the second and third terms represent the energy change associated with adsorption or desorption process, and the rest terms are the energy due to the mass transfer. UA is the overall conductance between the adsorber and the fluid delivered by the flow control unit (Figure 1). The temperature of the fluid, T_{FCU}, varies every half cycle of the operation between the temperature of the heat source ($T_{desorption}$) used to drive the system and the temperature of the fluid to which heat is rejected ($T_{adsorption}$). β is the ratio of the enthalpy of adsorption to the enthalpy of vaporization (h_{fg}), and is derived based on the Clapeyron equation using the equilibrium data of water in zeolite.

The thermal mass of the evaporator and condenser are neglected in the model because the thermal reaction time of the heat exchangers is significantly shorter than that of the adsorber and the transient response of the system are dominated by the process in the adsorber. Energy conservation in the evaporator and condenser is expressed as:

$$\dot{Q}_{evap} = \dot{m}_{evap} h_{fg} \quad (7)$$

$$\dot{Q}_{evap} = \frac{T_{cab} - T_{evap}}{R_{evap}} \quad (8)$$

$$\dot{Q}_{cond} = \dot{m}_{cond} h_{fg} \quad (9)$$

$$\dot{Q}_{cond} = \frac{T_{cond} - T_{amb}}{R_{cond}} \quad (10)$$

where R_{evap} and R_{cond} are the heat transfer resistance, and h_{fg} is evaluated at T_{evap} in equation (6) and at T_{cond} in equation (7).The heat into the system is defined as positive. The heat required to drive the system is

$$Q_{desorption} = 2\int_0^{half-cyle\ (desorption)} \dot{Q}_{adsorber}\, dt \quad (11)$$

The cooling provided to the vehicle is

$$Q_{evap} = 2\int_0^{half-cyle\ (adsorption)} \dot{Q}_{evap} dt \qquad (12)$$

The COP of the adsorption system is

$$COP = \frac{Q_{evap}}{Q_{desorption}} \qquad (13)$$

Cooling capacity of the system can be increased by using more than one adsorber. Multiple adsorbers work together and operate alternatively between desorption and adsorption phases to meet the cooling requirement of the vehicle. The number of adsorbers needed is calculated by

$$adsorber\ \# = \frac{UA_{cab}(T_{amb}-T_{cab})(cycle\ period)}{Q_{evap}} \qquad (14)$$

Two values of UA_{cab} are used for the cab of a commercially available class-8 truck ($UA_{cab,worst}$) and the cab with energy saving equipment ($UA_{cab,best}$) (Rugh and Farrington,2008). The parameters used in the model such as the properties of zeolite and water (Parsons *et al.* 1987, Menard *et al.* 2005), thermal resistance and temperatures are listed in Table 1. Six operating cycle (cycle periods of 20 minutes, 30 minutes, 40 minutes, 60 minutes, 100 minutes and 120 minutes) are simulated for the system to explore the optimal operation and control strategy.

Table 1 Table of Parameters Used in the Model

Parameter	Value	Parameter	Value
Diffusivity (zeolite-water)	2.9 x10^{-10} m^2/s	R_{evap} and R_{cond}	5 x10^{-3} °C/W
Sorbent mass per adsorber	1.0 kg	UA_{sorb}	19.4 W/°C
Sorbent bean diameter	2.0 mm	T_{cab}	23.0 °C
Vapor volume per adsorber	0.1 m^3	$T_{adsorption}$ and T_{amb}	38.0 °C
Specific heat of water	4210.0 J/kg-°C	$T_{desorption}$	250.0 °C
Specific heat of sorbent	920.0 J/kg-°C	$UA_{cab,best}$	37.5 W/°C
R_{flow}	324.6 kPa-s/kg	$UA_{cab,worst}$	65 W/°C

4. RESULTS AND DISCUSSION

4.1 System Performance

The results of a single adsorber and the heat exchanger connected to it are presented to represent the system performance, because the two adsorbers operate alternatively in the adsorption and desorption modes. The connected heat exchanger either serves as a condenser during the desorption process or as an evaporator in the adsorption phase. The system with an operating cycle of 30 minutes is used to demonstrate the system performance in Figure 2 and the characteristics of the system operating with different cycle periods are summarized in Table 2. As shown in Figure 2, during the first 15 minutes, half of the operating cycle, heat is supplied to the adsorber from the heat source. The adsorber operates in the desorption mode and is connected to the condenser. At the 15^{th} minute, the source of the fluid to the adsorber is switched to the heat sink and T_{FCU} changes from the 250°C to 38°C. During the second 15 minutes, the adsorber is cooled and adsorbs water from the evaporator. The procedure repeats and the sign of $\dot{Q}$ in Figure 2(a) is defined by the direction of the heat: positive sign indicates heat into the adsorber or the evaporator, and the negative sign means heat flowing out of the system.

The heat transferred between the sorbent and its surrounding is observed to reach the maximum at the beginning of each half cycle, and correspondingly a rapid temperature change occurs in the adsorber as shown in Figure 2(a) and (b). For instance, during the first 15^{th} minute, the heat into the sorbent reaches its maximum value within approximately 2 minutes and temperature of the sorbent increases from 38°C to 135°C. That is, the rate of temperature increase is approximately 48.5°C/minute, 3.7 times of the average rate of temperature increase (i.e. 13.2°C/minute) over this entire desorption process. Similar trend is observed in the adsorption phase and on the heat exchanger. This behavior may provide design guidance for the control algorithm of this system. For example, the flow rate of the fluid to cool the condenser and the adsorber should be adjusted to match the required heat transfer rate. This temporal adjustment would result in energy saving on pumps and fans, which is important when the engine is off and the fluid control unit is powered by the batteries.

The mass transfer between the water and the sorbent in the adsorber versus time is shown in Figure 3(c). $Y_{sorb,eq}$ is the equilibrium concentration of the adsorbed water in the dry sorbent and thus is the maximum concentration possible for the given temperature and pressure of the sorbent. However, it is not possible for the system to reach thermal equilibrium given the finite period of time, thus the adsorbed water concentration Y_{sorb} is smaller than $Y_{sorb,eq}$: the difference between Y_{sorb} and $Y_{sorb,eq}$ reaches the maximum around 2nd minute after the start of every half cycle and then this difference decreases. The longer the cycle period, the smaller the difference between Y_{sorb} and $Y_{sorb,eq}$ and the system is closer to the thermal equilibrium.

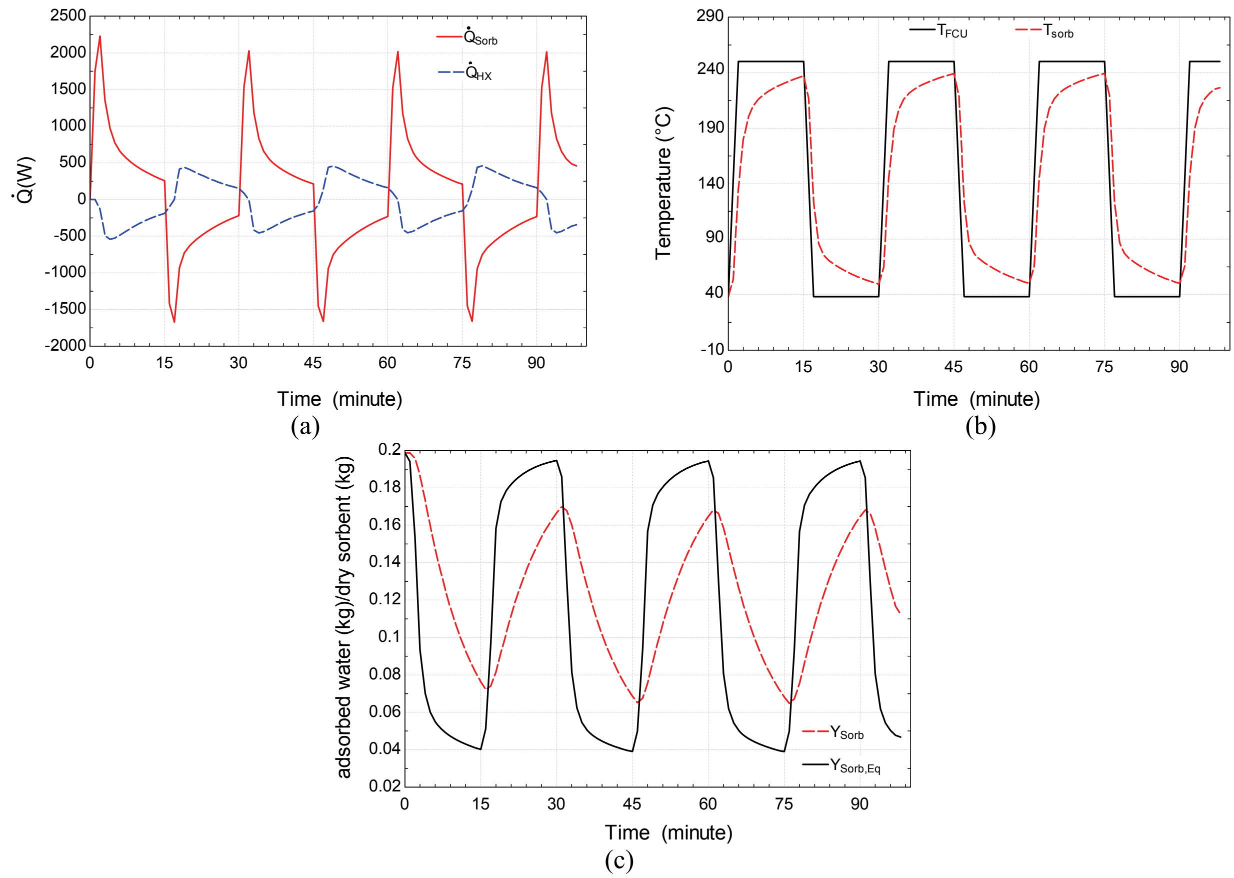


Figure 2 Transient performance of an adsorber and its attached heat exchanger (cycle period: 30 minutes)

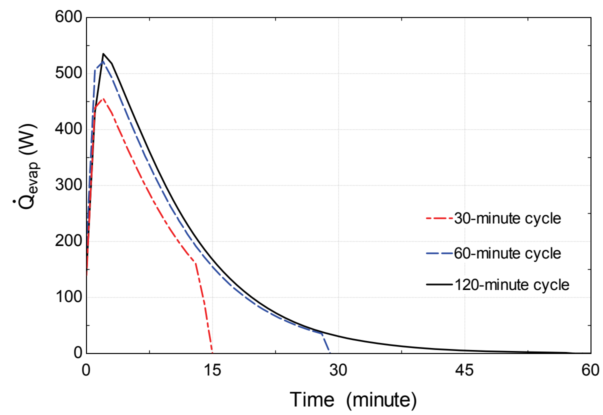
4.2 System with Different Operating Cycles

The operating cycle of the system can be managed by the fluid control unit and the effect of various cycle periods is shown in Table 2 and Figure 3. The COP of the system increases with the length of the cycle period; however, the total cooling capacity decreases during the same period of operation. For instance, the COP of the system with 20-minute cycle is 0.230, 46% of that if the two adsorbers operate with a 120-minute cycle. However, for a 120-minute operation, the system with 20-minute cycle has four complete cycles, and thus its total cooling capacity is 1158 kJ; the system with 120-minute cycle has one complete cycle and thus it provides a cooling of 808 kJ, 70% of that if the adsorbers switch their functions every 20 minutes. The system with short cycle period requires frequent change of the fluid flow between heat source and heat sink and has low COP, but it provides large cooling capacity to the cab for the same operating period.

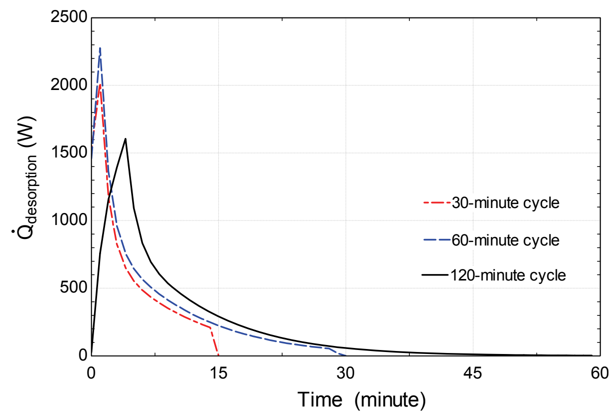
The heat and mass transfer of the system with different operating cycles are demonstrated in Figure 3. The general trend of the system performance for various cycle periods is similar and the maximum values of the heat transfer rate are listed in Table 2. The heat transfer rates reach a maximum shortly after the cycle starts. $\dot{Q}_{evap}$ is smaller for the system with shorter cycle period, but decreases at a similar rate. For instance, the average decreasing rate of $\dot{Q}_{evap}$ from 4th minute to 14th minute in Figure 3(a) is approximately 36W/minute, 32W/minute and 33W/minute for 30-minute, 60-minute and 120-minute cycles, respectively. During the desorption process, the heat transferred to the adsorber, $\dot{Q}_{desorption}$, is similar for the 30-minute and 60-minute cycles (Figure 3(b)). The trend of mass transfer in the adsorber is similar for different operating cycles (Figure 3(c)). The system with long cycle period tends to reach the thermal equilibrium concentration as the process continues; however, the rate of change in the concentration (Y_{sorb}) becomes insignificant: 24% decrease from the 30th minute to 60th minutes for the 120-minute cycle. This behavior indicates that desorption and adsorption of water vapor in the adsorber becomes inefficient and continuous operation is unnecessary. Hence, the system should avoid operating more than 30 minutes per half cycle.

Table 2 Characteristics of the system with different operating cycles

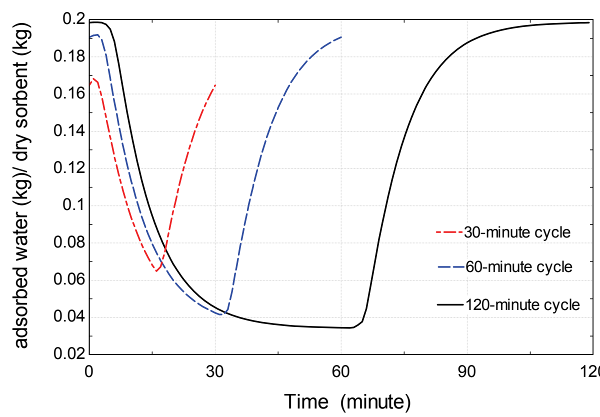
Cycle period (minute)	COP	Q_{evap} (kJ)	$Q_{desorption}$ (kJ)	$\dot{Q}_{evap,max}$ (W)	$\dot{Q}_{desorption,max}$ (W)	adsorber # $(UA_{cab,best})$	adsorber # $(UA_{cab,worst})$
20	0.230	289	1261	349	3306	1.9	3.2
30	0.436	508	1166	457	2015	1.6	2.8
40	0.448	614	1371	493	2605	1.8	3.0
60	0.487	740	1520	522	2276	2.2	3.8
100	0.492	803	1630	536	1775	3.4	5.8
120	0.498	808	1623	535	1605	4.0	7.0



(a)



(b)



(c)

Figure 3 Heat and mass transfer characteristics of the system operating with different cycle periods

When the system operates with 30-minute cycle period, the number of the adsorbers required is minimum. The cooling requirement is 780W for a commercially available class-8 heavy-diesel truck and 450W for the one with energy saving equipments. When the length of operating cycle increases, the number of the adsorbers required increases. This is mainly because the mass transfer of the water in the sorbent becomes ineffective about 30 minutes after the process starts. Due to the temporary variation of the heat transfer rate, it is important to control the operation of the adsorbers. For example, two adsorbers are required to work simultaneously for a system with 30-minute cycle period to provide cooling for the vehicle with energy saving equipments. However, these two adsorbers should not start the adsorption phase at the same time. The starting point of the adsorbers should be different in order to provide the instantaneous cooling of 450W for the vehicle. The control algorithm of the system based on the transient performance is important to minimize the number of adsorbers and thus the size of the system.

5. CONCLUSIONS

An adsorption air-conditioning system is studied for heavy-duty vehicle application. This system can reduce engine emissions and improve the overall engine efficiency. A model of the system using zeolite and water as working pair is developed and the system performance with various operating cycles is reported. The results show that the system with short cycle period requires frequent change of the fluid flow between heat source and heat sink and has low COP, but it provides large cooling capacity to the vehicle for the same period of time. An optimal cycle period exists because of the inefficient mass transfer of water in the sorbent after a certain period (approximately 30 minutes after the process starts). The dynamic performance is important to determine the control algorithm order to minimize the number of adsorbers and to reduce the energy consumption on pumps and fans when the engine is off and the fluid control unit is powered by the batteries.

NOMENCLATURE

m	mass	(kg)	**Subscripts**	
t	time	(second)	vapor	vapor phase
P	pressure	(Pa)	sorb,s	sorbent
T	temperature	(°C)	evap	evaporator
u	specific internal energy	(J/kg)	cond	condenser
h	specific enthalpy	(J/kg)	liquid	liquid phase
Cv	specific heat	(J/kg-K)	amb	ambient
UA	heat conductance	(W/K)	cab	cab of the vehicle
Y	ratio of adsorbed water to dry sorbent			

REFERENCES

Agnew, B.,Talbi,M., Mostafavi. M., 1999. Combined power and cooling, an analysis of the combined diesel-absorption cycle. *Applied Thermal Engineering*, 19: p.1097-1105.

Ainslie, B., Rideout, G., Cooper, C., Mckinnon. D., 1999. The impact of retrofit exhaust control technologies on emissions from heavy-duty diesel construction equipment. *SAE International Congress and Exposition*, Detroit, Michigan, SAE paper no.1999-01-0110.

Davis, S.C., Diegel, S. W., Boundy. R.G., 2008. *Transportation Energy Data Book*, Edition 28. Oak Ridge National Laboratory, ORNL-6984.

EPA(http://www.epa.gov/). 2009. Regulations and Standards. U.S. Environmental Protection Agency, Office of Transportation and Air Quality.

Gaines, L., Vyas, A., Anderson J.L.,. 2006. Estimation of fuel use by idling commercial trucks, *85th Annual Meeting of Transportation Research Board*, Washington D.C., Paper No.06-2567.

Giannelli, R.A., Nam. E., 2004. Medium and heavy duty diesel vehicle modeling using a fuel consumption methodology. *US EPA NVFEL*, Ann Arbor, MI.

Gorbach, A., Stegmaier, M., Eigenberger. G., 2004. Measurement and modeling of water vapor adsorption on zeolite 4A - equilibria and kinetics. *Adsorption* 10: 29-46.

Hendricks, T.J., Lustbader. J. A., 2002. Advanced thermoelectric power system investigations for light-duty and heavy-duty applications: part II. *21st International Conference on Thermoelectronics*, Long Beach CA, 387-394.
Herner, J.D., Hu, S., Robertson, W.H., Huai, T., Collins, J.F., Dwyer, H., Ayala A. 2009. Effect of advanced aftertreatment for PM and NOx control on heavy-duty diesel truck emissions. *Environ. Sci. Technol*., 45:5928-5933.
Lambert, M.A., Jones B.J.. 2006a. Automotive adsorption air conditioner powered by exhaust heat. Part 1: conceptual and embodiment design. *Proceedings of the Institution of Mechanical Engineers Part D: J. Automobile Engineering*, Vol.220 p.959-972.
Lambert,M.A., Jones B.J.,. 2006b. Automotive adsorption air conditioner powered by exhaust heat. part2: detailed design and analysis. *Proceedings of the Institution of Mechanical Engineers Part D: J. Automobile Engineering*, Vol.220 p.973-989.
Menard, D., Py, X., Mazet N.,. 2005. Activated carbon monolith of high thermal conductivity for adsorption processes improvement part A: adsorption step. *Chemical Engineering and Processing*, 44: 1029-1038.
Parsons, B.K., Pesaran, A.A., Bharathan, D., Shelpuk S., 1987.*Evaluation of thermoally activated heat pump/desiccant air conditioning systems and components.* Oak Ridge National Laboratory, SERI/TR-252-3116.
Rugh, J., Farrington, R., 2008. *Vehicle Ancillary Load Reduction Project Close-Out Report,* National Renewable Energy Laboratory, Technical Report NREL/TP-540-42454.
Stolz, A., Fleischer, K., Knecht, W., Nies, J., Strahle R., 2001. Development of EGR coolers for truck and passenger car application. *Society of Automotive Engineers*, *Inc. SAE paper no. 2001-01-1748*.
Talbi,M., Agnew B., 2002. Energy recovery from diesel engine exhaust gases for performance enhancement and air conditioning. *Applied Thermal Engineering*, 22: 693-702.
Wang, R.Z., Oliveira R.G., 2006. Adsorption refrigeration – an efficient way to make good use of waste heat and solar energy. *Progress in Energy and Combustion Science*, 32:p.424-458.
Zhang, L.Z. 2000. Design and testing of an automobile waste heat adsorption cooling system. *Applied Thermal Engineering*, 20:p.103-114.