An innovative design of temperature control based on controllable heat pipes

Новаторская конструкция контроля температуры основанная на контролировать трубах жары

JIANG Jibing†*, PENG Weiwei†, TIAN Kan†

Цзян Кыргызстан солдат,Пэн микро - Вэй,тянь пронзать

†Master,China-EU Institute for Clean and Renewable Energy, Huazhong University of Science & Technology, 1037 Luoyu Road, Wuhan, 430074, China

магистр ,Центральной института чистых и возобновляемых источников энергии ,в хуа жонге, университет,1037Ло Ю Лу,Ухань,430074,китай

*Corresponding Author. E-mail: jjb921986@hust.edu.cn; Tel.: +86 186-9616-4906

Автор сообщения. Почтовый ящик: jjb921986@hust.edu.cn;Телефон: +86 186-9616-4906

Index UDC: 536.2

Absrtact

Selective Catalyst Reduction(SCR) have been demonstrated as an efficient technology for the abatement of NO_x emissions from diesel vehicles. However, the challenges created by the transient characteristic of vehicle operating condition are increasing, particularly, to meet the stringent exhaust emission regulation. The exhaust temperature, which directly decide the performance of catalytic and limitation of practical application, is regarded as the origin of research difficulty and complexity. An innovative design based on the controllable heat pipes and latent thermal energy storage is proposed in this study to stabilize the fluctuation of exhaust temperature and realize thermal management. Which are installed in the upstream of SCR system. The excess energy will be storaged by the phase change material absorbing spontaneously during the high temperature and release to keep small variation for low temperature. In order to eliminate the localization of temperature control, the fuzzy adaptive control algorithm will be adopted to improve the robustness. The simulation results show that the device demand 25s-30s for cold start in the test of European transient cycle. The robustness can be confined to ±20℃after finish the cold start. The experimental investigation demonstrated that compared with the original condition, the meliorative efficiency of NO_x elimination can keep more than 95% in the sample engine. The SCR system operated in the narrow temperature window. Not only avoid the low N2 selectivity and ageing issue at high temperature, but still keep in high NO_x reduction efficiency with low exhaust temperature.

Keywords: Selective Catalyst Reduction(SCR), controllable heat pipes,temperature control NOx reduction

Резюме

Селективное уменьшение катализатора было продемонстрировано как эффективная технология для abatement излучений NO_x от тепловозных кораблей. Однако, возможности созданные переходной характеристикой условия эксплуатации корабля увеличивают, определенно, для того чтобы встретить stringent регулировку излучения вытыхания. Температура вытыхания, которые сразу решают характеристику рабочое каталитических и ограничение практического применения, сосчитана как начало затруднения и сложности исследования. Предложены, что в этом изучении стабилизирует зыбкость температуры вытыхания и осуществляет новаторская конструкция основанная на controllable трубах жары и скрытом термально хранении энергии термально управление. Установлены в upstream of система SCR. Сверхнормальная энергия будет storaged материалом изменения участка поглощая самопроизвольно во время high-temperature и отпуска для того чтобы держать малое изменение для низкой температуры. Для того чтобы исключить локализацию контроля температуры, пушистый алгоритм адаптивного управления будет принят для того чтобы улучшить робастность. Результаты имитации показывают что требование 25s-30s приспособления для начального пуска в испытании европейского переходного цикла. Робастность можно ограничить к отделке ±20 ℃ after начальный пуск. Экспериментально исследование продемонстрировало то сравненное с первоначально состоянием, meliorative эффективность исключения NOx может держать больше чем 95% в двигателе образца. Система SCR работала в узком окне температуры. Not only избегите низкой селективности N_2 и старея вопроса на high-temperature, но все еще сдержите в высокой эффективности уменьшения NO_x с низкой температурой вытыхания.

ключевые слова: контроль температуры, контролировать труба жары, Селективное уменьшение катализатора, NO_x уменьшение.

1. Introduction

It is well known that the nitrogen oxide (NO_x) emissions to the environment has caused serious negative impact on climate change and human health, in details, NO_x emission has directly or indirectly caused a series of serious problems such as acid rain, photochemical smog and human diseases, which are received more and more attention by worldwide researchers. It is reported that 30% of NO_x emission comes from automobile exhaust gas and the need to mitigate NO_x emissions by developing novel emission reduction technology is now widely accepted. China was contributed to the biggest consumer market of automobile with the trading volume of 22 millions in 2013. Therefore, it is pressing for China to control the NO_x emission of automobile. Compared the China's inventory and NO_x emission contribution of various types of vehicles in 2012, which are shown in Figure 1, it can be found that medium-type and heavy-type vehicles are only accounted for approximately 12% in total vehicles, but the NO_x emission contribution of them are as high as approximately 85% in total vehicles. What is more, the inventory of medium and heavy diesel vehicles in China kept a stable increasing from 2009 to 2012, and accounted for an increasing proportion in total vehicles, which illustrated that it is of great importance to control the pollutant emission of medium and heavy diesel vehicles to realize the NO_x emissions of vehicles in China.

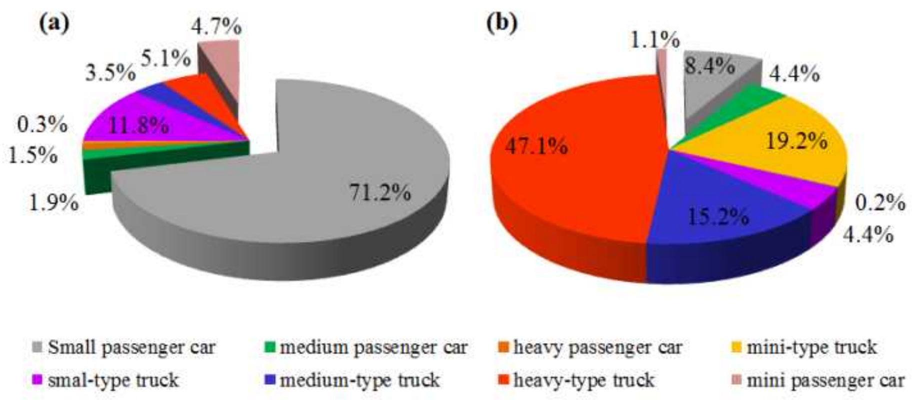

Figure 1 Distribution of China's inventory and NO_x emission of various types of vehicles in 2012

As for NO_x emission reduction of medium and heavy diesel vehicles, Selective Catalytic Reduction (SCR) technology is one of the most widely accepted technologies nowadays due to its outstanding advantages of high efficiency of NO_x emission reduction, small secondary pollution and mature technique. Although many researches paid enormous effort on improving NO_x conversion efficiency, it is performed unsatisfactory NO_x conversion efficiency when operating on the transient conditions, which was attributed to the constantly changing of exhaust temperature and the unpredictable ammonia storage of catalyst. Therefore, many researches focused on the thermal management of exhaust by applying throttle valve, heat insulation measurement and fuel injection technology, the results proved that the exhaust temperature was effectively improved and helpful for the NO_x conversion efficiency at low-temperature working condition. However, it caused increasing fuel consumption and negative engine performance, what is more, The problems of cytalyst performance deterioration under high-temperature working condition and low efficiency under transient condition are not solved. The 7.1 L diesel engine, which is the common and widely used diesel model, is selected as our research object. As shown exhaust temperature distribution in ETC test of Figure 2 left and exhaust energy utilization of Figure 2 right, it can be found that the high temperature exhaust energy are contributed to a considerable amount in total exhaust energy. On addition, the effective utilization of heat only accounts for 38% ~ 42% in total quantity of heat, and exhaust gas recovery potential heat accounts for 10% ~ 15% in total quantity of heat, which presents the great recovery potential heat in vehicle exhaust. Therefore, an innovative device based on the controllable heat pipes and latent heat storage is proposed in this study to stabilize exhaust temperature fluctuation and realize thermal management. Our novel temperature control device not only is helpful for improving the NO_x conversion efficiency in diesel exhaust, but also can realize the recycle of exhaust energy, through which way the goal of energy conservation and emissions reduction can be achieved.

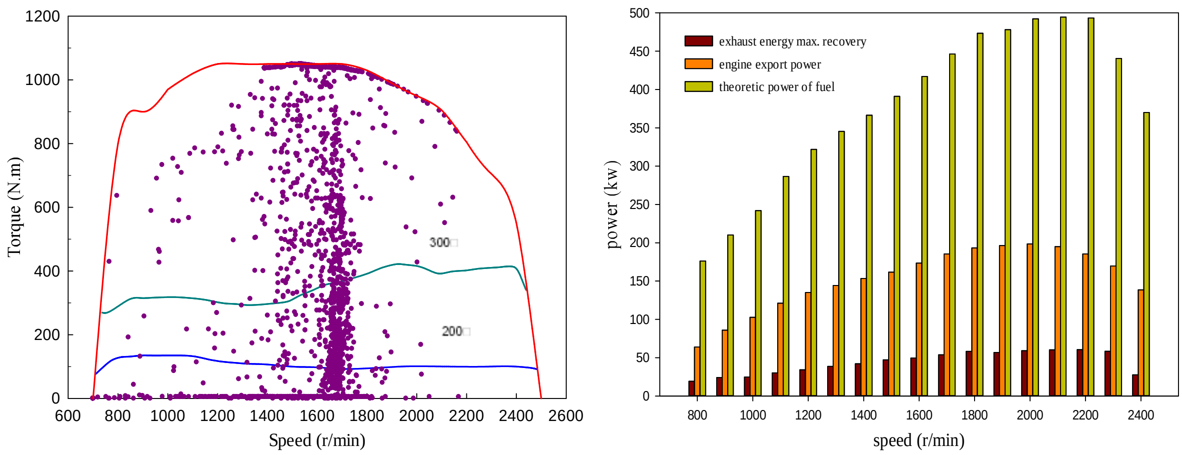

Figure 2 left. Exhaust temperature distribution after automotive turbochargers and ETC point; right. fuel utilization efficiency and exhaust recycle efficiency of automotive

2. Design of the temperature control system

2.1 Schematic diagram of temperature control system

Figure 3 shows the schematic diagram of the innovative device, it is expect that this innovative device can improve the NO_x conversion efficiency of diesel exhaust by controlling exhaust temperature. The temperature control system, which based on controllable heat pipe and phase change materials (PCM) storage, is mainly consisted of three parts: evaporation section, thermal storage section and condensation section. The heat of vehicle exhaust will transfer to the working fluid in controllable heat tube when vehicle exhaust passes away the tube bundles, and working fluid is heated and evaporate upward when reaching the melting point. Meanwhile, working fluid release heat to PCMs when facing with the cold energy storage section, then the high temperature evaporation compress the non-condensed gas, so that changing the heat transfer areas in heat tube to stabilize the outlet temperature of vehicle exhaust. In addition, the temperature signals as feed-forward and feed-back is reflected to the control unit to adjust the forced cooling quantity in condensation sector through installing the temperature sensors on the inlet and outlet of device, eventually to achieve the effect of controlled temperature.

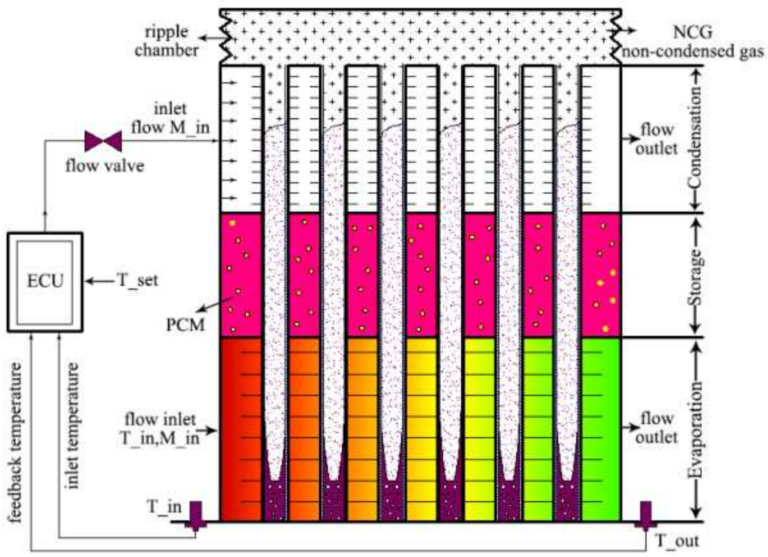

Figure 3 The schematic diagram of the innovative temperature control design

2.2 Phase Change Materials (PCMs) storage

Phase Change material (PCMs) is a special kind of functional material, it can change phase in the case of isothermal or approximate isothermal condition. The phase change process of PCMs is approximate constant temperature system, and the temperature of PCMs can be easily controlled, what's more, it can recycle energy and increase energy utilization, thus, this material is widely applied to the solar heat recovery, clothing engineering of temperature control, heat preservation, heat insulation materials and other fields.

Molten salt has become one of the best heat storage materials because of its low price, good conductivity and thermal stability; low energy consumption; high heat storage density and wide temperature range (from 150 °C to 1200 °C). It is reported that the temperature range of automobile exhaust is between 200 °C and 600 °C, the thermal properties of molten salt materials commonly used in this temperature range as shown in table 1.

Table 1 Thermal properties of phase change materials

material	melting temperature/℃	ablation heat ($kJ\cdot kg^{-1}$)	heat conductivity ($W\cdot (m\cdot k)^{-1}$)	Density ($kg\cdot m^{-3}$)
$NaNO_3$	307	172	0.50	2260
68.1%KCl+31.9%ZnC_2	235	198	0.8	2480
$LiNO_3$	254	365	0.8	2380

For diesel NO_X emissions reduction, Selective Catalyst Reduction (SCR) is the most common used technology: NH_3 is adsorbed on the active sites of catalysts, and then react with NO_x in the exhaust gas to generate N_2 and H_2O. Copper-based, vanadium-based, iron-based catalysts are the most common choices of SCR catalysts, each catalyst have its own temperature window of the highest catalytic efficiency. If the SCR reaction temperature can be strictly controlled in the window, then the efficiency can be greatly improved. Table 2 shows the catalyst temperature window and exhaust temperature range of bus and heavy truck. We select bus and heavy truck as our research object under actual working conditions, choosing 280 °C as control temperature, respectively. Comparing with the melting temperature of phase change materials, 68.1%KCl+31.9%$ZnCl_2$ and $LiNO_3$ are selected to realize heat storage in heat pipe.

Table 2 Working temperature window

The working conditions	Copper base catalyst	Vanadium catalyst	Iron-based catalyst	NH_3 atomization	Actual working condition - bus	Actual working condition - truck
temperature/℃	200-300	250-400	400-500	>250	120-400	150-580

However, phase change materials are greatly limited for thermal response rate and total efficiency of thermal energy storage system because of its low conductivity coefficient. The improvement of phase change materials becomes a key issue of our work.

2.3 Temperature control unit

Fuzzy adaptive control is the mainstream control algorithm in the industry technology, and fuzzy adaptive PID control algorithm is used in our temperature control unit, which can be seen from Figure 4.

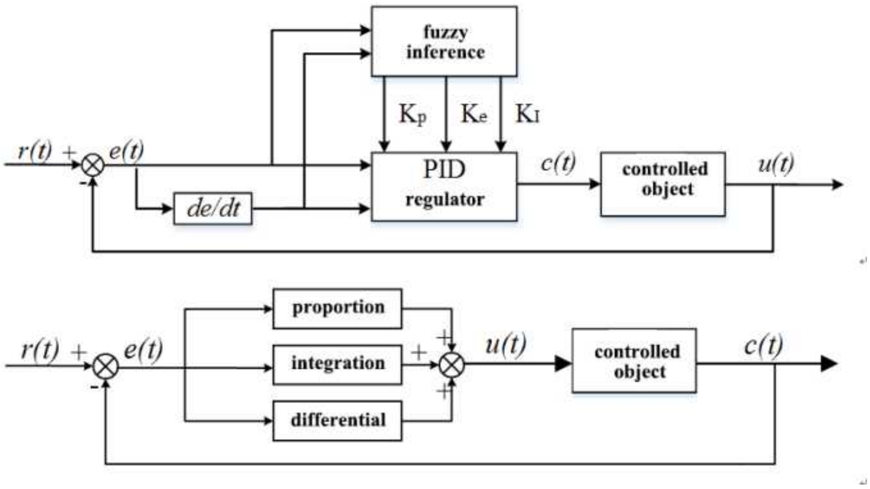

Figure 4 Schematic diagram of fuzzy adaptive PID control algorithm

Characteristic parameters of control object changes along with the real-time transform of working environment in heat pipe and the influence of interference factors, adaptive control algorithm can online identify the real-time change characteristic parameters to adjust control strategy by modern control theory, so that making sure the performance index of system in the optimal range. Because of the indefinite quantity of semaphores in control process, fuzzy adaptive PID control algorithm is used for reaching optimal adjustment. Finally, the temperature control can be achieved by control reasonable forced cooling amount in condensation section.

3. Theoretical analysis and simulated analysis

Figure 5(a) shows the two-phase flow model in heat pipe micro-channel, and the heat pipe heat transfer model can be established according to two-phase flow model. Figure 5(b) shows energy path diagram of temperature control device, which provide the basic model of temperature control system. Thus, temperature control can be realized based on these two model and intelligent control algorithms.

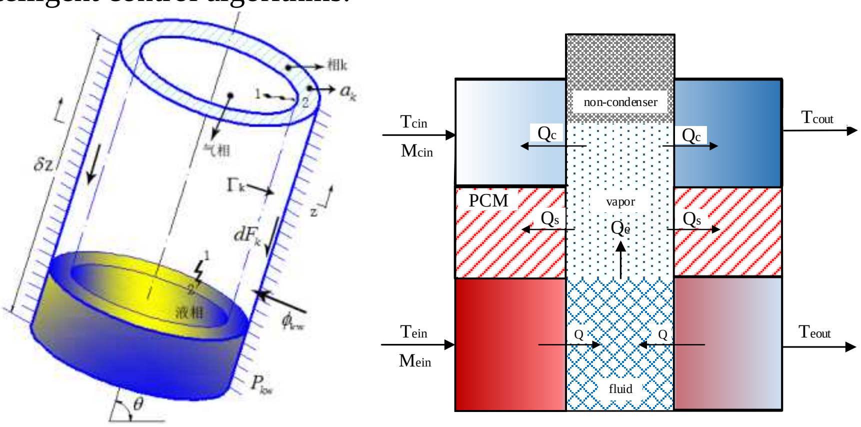

Figure 5 (a) Two-phase flow model in heat pipe micro-channel; (b) Energy path diagram of temperature control device

When two-phase working fluid is at steady state:

$$\begin{cases} \frac{\partial}{\partial z}(A\rho_g \upsilon_g) = \Gamma_g \\ \frac{\partial}{\partial z}(A\rho_f \upsilon_f) = \Gamma_f \end{cases} \quad (1)$$

At condensation section, $\Gamma_k = 0$. Variation of steam mass is equal to total condensation mass of molecular per second, i.e. $\Gamma_g = \Gamma_f$

$$\begin{cases} \Gamma_g = N_{v,l} = \pi R_v^2 \dfrac{P_v}{m\upsilon_{av}} \sqrt{\dfrac{3}{2\pi}} & \dfrac{dm_v^{'}}{dx} = \dfrac{\pi R_v^2 P_v}{\sqrt{2\pi R_g T_l}} \\ \upsilon_{ac} = \sqrt{\dfrac{3kT_l}{m}} = \sqrt{3R_g T_l} & \Downarrow \\ \Gamma_f = m_v^{'} = A\rho D \dfrac{d \ln \chi_g}{dx} & A\rho D \dfrac{d^2 \ln \chi_g}{dx^2} = \dfrac{\pi R_v^2 P_v}{\sqrt{2\pi R_g T_l}} \end{cases} \tag{2}$$

Momentum conservation equation of gas phase is listed as follows:

$$-A_g \frac{\partial p_g}{\partial z} - \tau_{gf} P_{gf} - A_g \rho_g g \sin\theta + \upsilon_g \Gamma_g = \frac{\partial}{\partial z}(m_g \upsilon_g) \tag{3}$$

Momentum conservation equation of liquid phase is listed as follows:

$$-A_g \frac{\partial p_g}{\partial z} - \tau_{gf} P_{gf} - A_g \rho_g g \sin\theta + \upsilon_g \Gamma_g = \frac{\partial}{\partial z}(m_g \upsilon_g) \tag{4}$$

When boiling and condensation correction coefficient of heat transfer are used in energy conservation equation:

$$\mathrm{h_b} = [(0.485 \times 10^{-4})(T_{\mathrm{s\_evap}} - T_{\mathrm{int\_fluid}})^{-0.07675} \times (\frac{C_{pl}\mu_l}{k_l})^{0.6857} T_{sat}^{3.291}]^{0.9287} \tag{5}$$

$$\mathrm{h_c} = 0.01074 Re^{-2.667} T_{sat}^{4.30} \tag{6}$$

The Reynolds number used in equation (5) can be described as follows:

$$\mathrm{Re} = 2.5872 \times \frac{4}{3} \frac{2kl(T_{\mathrm{int\_fluid}} - T_{\mathrm{s\_cond}})d}{\mu h f_g} \left[\frac{4(\rho_l - \rho_v)g}{3\rho_l(\mu / \rho_l)^2} \right]^{1/3} \tag{7}$$

The Expression of evaporation and condensation heat resistance:

$$\sum R_{evap} = \frac{1}{h_e A_e} = \frac{\ln(d_o / d_i)}{2\pi kl} + \frac{1}{h_b A_b} \tag{8}$$

$$\sum R_{cond} = \frac{1}{h_c A_c} = \frac{\ln(d_o / d_i)}{2\pi kl} + \frac{1}{h_c A_c} \tag{9}$$

When the temperature of working fluid in heat pipe is small than saturation temperature, that is to say, $T_f \le 257$ °C:

$$MC_p \frac{dT_g}{dt} = M_e C_p (T_{in} - T_{out}) - Q \tag{10}$$

And $T_g = \dfrac{T_{in} + T_{out}}{2}, Q = \dfrac{T_g - T_f}{2R} = m_f C_{pf} \dfrac{dT_f}{dt}$

The moment when the temperature of working fluid in heat pipe is equal to 275 °C is defined as t_1:

$$MC_p\frac{dT_g}{dt}=M_eC_p(T_{in}-T_{out})-Q \tag{11}$$

And $T_g=\frac{T_{in}+T_{out}}{2}$, $Q=\frac{T_g-T_f}{2R}=mvQ_{latent}$, $Q_{latent}=296.4kJ/kg$

When $Q_s=m_sQ_{latent}$, $\frac{\int_{t_1}^{t_2}(m_o-m_s)dt}{\rho}=V_s$, the moment is defined as t_2.

It is noted that the intelligent control system start to work when $t>t_2$, and $Q=Q_c+Q_s+\frac{dm_v}{dt}C_{pv}T_{sat}$, Q_c is adjusted by intelligent algorithm.

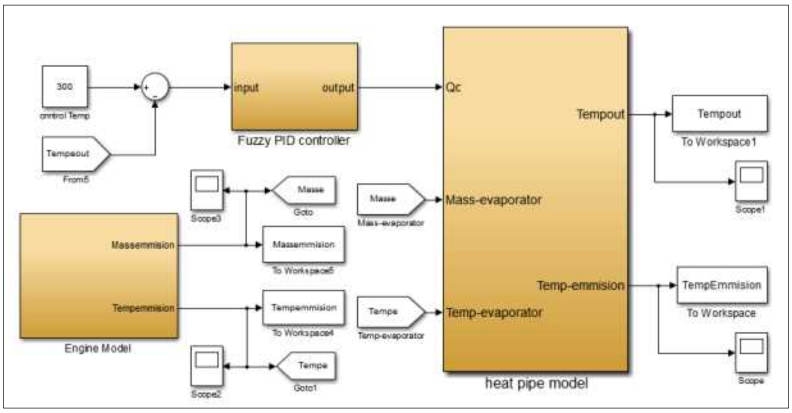

Figure 6 Temperature control model based on Matlab/Simulink software

As is shown in Figure 6, it can be found that temperature control system is consisted of three parts: exhaust temperature and mass flow provided by engine model, temperature control model and fuzzy adaptive control unit.The temperature control results can be achieved according to the preliminary simulation models, As shown in Figure 7, when considering the cold start effect of temperature control system, the working fluid need a certain time to reach the saturation condition, thus, the outlet temperature of temperature control system is relatively low at first stage, and the decrease rate of exhaust temperature will be slow along with the increasing temperature of working fluid. It can be found from Figure 7 that the cold start process can be finished within 25 s. Figure 8 shows temperature control results when not considering priming effect in heat pipe, the working fluid already reach the saturation state during operating process without considering the cold start, which is contributed to the satisfactory temperature control results. It can be explained as follows: firstly, the evaporation chamber in temperature control system can effectively realize the temperature neutralize so that can reduce the temperature fluctuation; secondly, the adjustment of temperature control system is helpful to the satisfactory results. As for the control effect, it can be found that the temperature control error is within ±20 °C, meaning the exhaust temperature is near to steady state, it is contributed to simple control strategy of SCR system and small calibration workload. Figure 9 shows NOx concentration distributions under three different conditions, the NOx conversion efficiency can be larger than 95 % after using temperature control system, which conform to the Euro 6 emission standards.

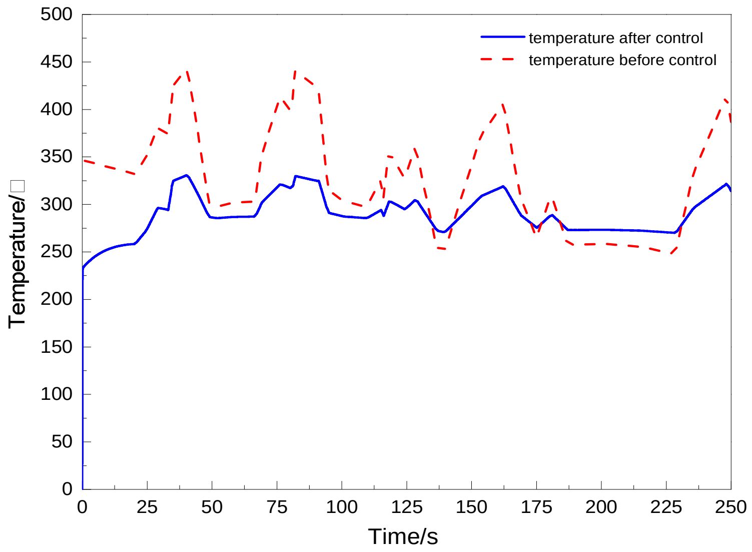

Figure 7 Temperature control results when considering cold starting effect in heat pipe

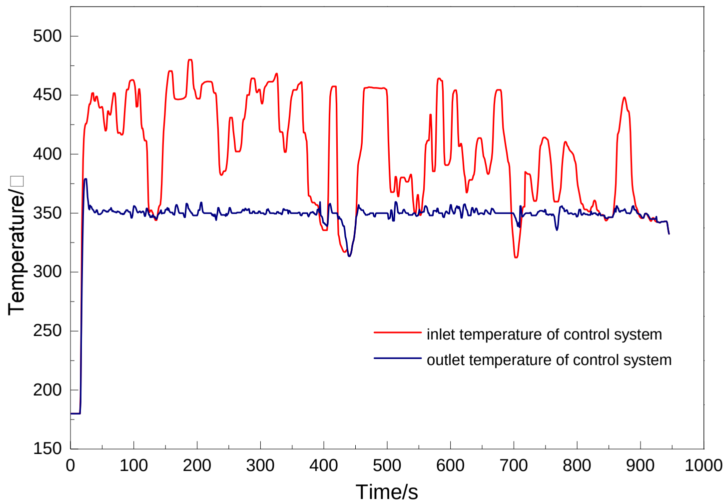

Figure 8 Temperature control results when not considering priming effect in heat pipe

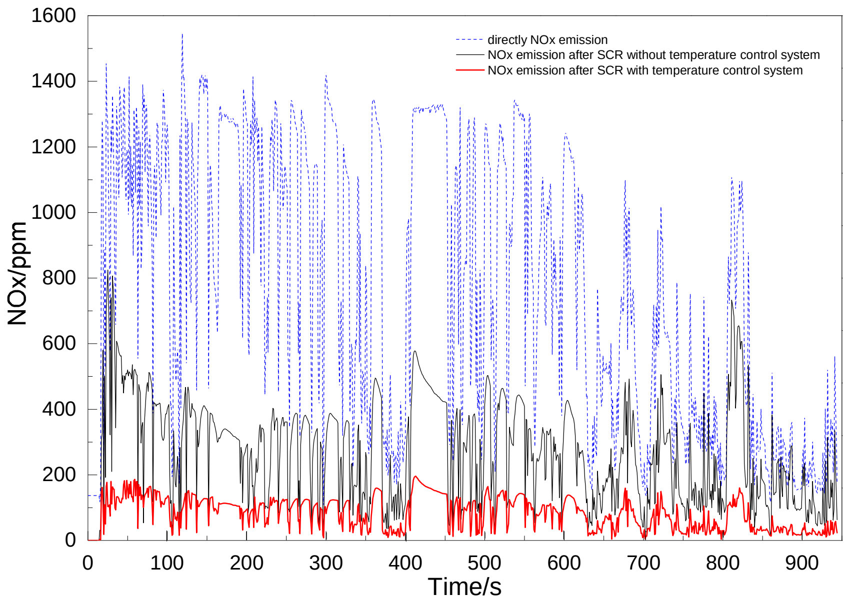

Figure 9 NO_x concentration distributions under three different conditions

4. Economic Analysis

According to market research, the price of our innovative temperature control device made to order is about 2000 Yuan and Nanjing saint carnot heat pipe company agree with our price. Average quantity of heat recycled from the controllable heat pump system is about 5 Kilo Watts. Considering the manufacturing cost and energy conservation and emission reduction of middle and heavy trucks, this price is acceptable, and the middle and heavy trucks have enough space for installing the temperature control device. Take King Long XMQ614OY8 bus (69 seats) for example, economic analysis shown in the following table, and the heat recycled from the controllable heat pump installed in the tail gas treatment system is used to heat drinking water and to drive air condition system.

Table 3 Economic analysis of automobile exhaust using for heating drinking water

Using for heating drinking water (20 °C -100 °C)			
Electricity consumption (kWh/L)	Daily demand of drinking water (L)	Daily power demand (kWh)	Annual electric charge (yuan)
0.093	55	55*0.093=5.13	5.13*0.42*356=786

Table 4 Economic analysis of automobile exhaust using for driving air condition system

Using for driving air condition system						
Output power of air condition system (kW)	Daily working time (h)	Annual operating time（day）	Annual energy saving（kW）	Transfer efficiency	Annual gasoline saving（L）	Annual cost saving（元）
4	8	240	7680	40%	2125	425

According to the data from 2013 National Bureau of Statistics, the NO_x emission amount of China in 2013 is 6406 kiloton, in which middle and heavy truck take account for 75.9%, i.e. 4862 kiloton. If our temperature control device can apply in middle and heavy truck, the NO_x emission amount can reduce to 1519 kiloton, the calculation is listed in Table 5.

Table 5 NO_x emission calculation after using temperature control device

Item	China Ⅳ standard	Using temperature control device	Reduced NO_x emission
NO_x conversion efficiency	68%	95%	3343 kiloton
NO_x emission amount/kiloton	4862	1519	

5. Innovations and applications

Innovations: (1) Temperature is used to measure the molecular motion intensity and control temperature is typical time delay system, heat pipe with high heat flux is used as control carrier in our device, which provides new idea for temperature control; (2) It is the first time that controllable heat pipe integrated with phase change material is used in after-treatment system of automobile exhaust gas, which can realize NO_x emission reduction and energy saving by effectively temperature control.

Applications: (1) In auto industry, middle and heavy diesel truck can use our innovative device to achieve high NO_x conversion efficiency and energy saving; (2) In solar power station, this device can be used for peak load shifting and control steam temperature; (3) In thermal power generation, steel smelting and waste incineration process, our innovative device can reduce NO_x emission and promote the green upgrade in industry.

Reference

[1] Mohammed M. Farida,Amar M. Khudhair, Siddique Ali K. Razack, Said Al-Hallaj, A review on phase change energy storage: materials and applications, Energy Conversion and Management 45 (2004) 1597–1615.

[2] Feldman D, Shapiro MM. Fatty acids and their mixtures as phase-change materials for thermal energy storage.Solar Energy Mater 1989；18:201–16.

[3] Hasan A. Phase change material energy storage system employing palmitic acid. Solar Energy 1994；52:143–54.

[4] Dimaano M, Escoto A. Preliminary assessment of a mixture of capric and lauric acid for low temperature thermal energy storage. Energy 1998；23:421–7.

[5] Farid MM, Hamad FA, Abu-Arabi M. Phase change cool storage using dimethyl-sulfoxide. Energy Convers Mgmt 1998；39:819–26.

[6] Zuca S, Pavel PM, Constantinescu M. Study of one dimensional solidification with free convection in infinite plate geometry. Energy Convers Mgmt 1999；40:261–71.

[7] Leonard L. Vasiliev, Review Heat pipes in modern heat exchangers, Applied Thermal Engineering 25 (2005) 1–19

[8] William G. Anderson, John R. Hartenstine, David B. Sarraf, Calin Tarau, and Kara L. Walker, Pressure Controlled Heat Pipe Applications, 16th International Heat Pipe Conference (16th IHPC) Lyon, France, May 20-24, 2012

[9] Stoval TK, Tomlinson JJ. What are the potential benefits of including latent storage in common wallboard? Trans ASME 1995；117:318–25.

[10] Y. Tian, C.Y. Zhao, A review of solar collectors and thermal energy storage in solar thermal applications, Applied Energy 104 (2013) 538–553.

[11] ZHANG Fei, JIAN Qi-fei, Waste Heat Utilization Technologies and Applications of Automobile Exhaust, 1674-3997-(2010)01-0043-03.

[12] N. Malatidis, Warmespeicher, insbesondere Latentwarmespeicher fur Kraftfahrzeuge, Patent DE39 90 275 C 1 (1988).