

Research Article

Research on the Working Performance of Carbonized Micro-wood Fiber DPF

Dan-feng Du, Jian Li and Xiu-rong Guo

Northeast Forestry University, Harbin, 150040, P.R. China

Abstract: Along with the increasingly stringent emissions regulations, the Diesel Particulate Filter (DPF) is one of the leading technologies for reducing particulate matter in diesel exhaust. In this study, it is presented that the Carbonized Micro-Wood Fiber (CMWF) is used as filter material of DPF. Firstly, the permeability and the inertia coefficient are obtained by numerical simulation method, then the geometric relationship between the $\Delta p/H$ (the ratio of a pressure difference of the front and back of a filter body and the thickness) and the v_1 (exhaust flow velocity in front of the filter body), lastly, the test is performed utilizing the self-designed detachable DPF and the flow characteristics test bed. Theory and test proves that the numerical simulation method can be consistent with the test very well, which shows the DPF with bigger pore diameter and longer axial length should take priority over the others.

Keywords: Carbonized Micro Wood Fiber (CMWF), Diesel Particulate Filter (DPF), inertia coefficient

INTRODUCTION

Along with the more and more strictly emission regulations, Diesel Particulate Filter (DPF) technology is one of the most effective and simple methods to control the diesel particulate emission ultimately (Juan *et al.*, 2009). The current DPF filter materials mainly include: cordierite honeycomb ceramics, ceramic foam, woven ceramic fiber, metal mesh, metal fiber, silicon carbide, silicon nitride, activated carbon fiber and so on, in which the most commonly used filter materials are cordierite and silicon carbide (Adler, 2005). However, in view of the specific national conditions of our country, the DPF filter materials always exist some kinds of shortcomings, so the vast majority of diesels will face the problem that they cannot run on the roads in their service lives if the Euro V standard is executed (Fang *et al.*, 2009; Li *et al.*, 2009; Wang *et al.*, 2010). In order to make our country's exhaust emission standards conforms with international ones as soon as possible, the researchers are spare no effort on new materials and new technology for diesel vehicle energy saving and emission reduction. Along with the development of the diesel engine machine cleaning technology, the particulate materials emitted by diesel engines become more and more small, a large number of studies show that these small particles are very harmful for human health (He *et al.*, 2007). Therefore, more and more countries pay attention to the small particulate emission and studies show that Carbonized

Micron Wood Fiber (CMWF) DPF is expected to become one of the effective methods to solve the problem of small particle emission in future.

The theory and experiment prove that, The DPF made by CMWF has high filtration efficiency, less exhaust back pressure and long service life, which open a new direction for the purification of diesel engine exhaust gas (Ma *et al.*, 2009).

The permeability and inertial of porous media are two important parameters related to the characteristics of fluid flow in the porous medium (ISO4022, 1977; Kaviany, 1991). Therefore, it is very important for the research on porous materials to determine the permeability and inertial coefficient of porous media exactly. In this study, the numerical simulation and experimental study of exhaust flow characteristics in CMWF DPF was investigated and the relationship of the permeability, inertial coefficient and $\Delta p/H$ (the ratio of the pressure difference to the material length) with v_1 (the gas flow velocity before filter material) was obtained, which could provide an effective basis for the structure design and the theory or experimental research.

CARBONIZED MICRON WOOD FIBER FILTER MATERIAL

Processing the high strength wood fiber to microns thickness can form micron wood fiber, then applying such micron wood fiber materials and other materials in appropriate proportion could form DPF



(a) Micron wood Fiber



(b) Carbonized micron wood fiber DPF filter

Fig. 1: Micron wood fiber and CMWF DPF filter

filter by a specific carbonization process, micron wood fiber and CMWF filter as shown in Fig. 1. In the research on lumber nano-micron processing technology, the restructure of fiber structure would change the arrangement shape of wood structure when the wood fiber is processed into the micron thickness, so the ultrathin processing method could apply to adjust make the wood fiber structure to increase the strength and toughness and the super finishing could apply to eliminate natural defect of wood itself (Ma, 2001; Ma *et al.*, 2003). Through depth carbonation by use some special method, micron wood fiber produced by this technology processing has not only high porosity, large specific surface area, faster adsorption desorption speed and larger adsorption capacity, but also different active functional groups on carhide surface, which have catalytic conversion function to pollutants and could also remove nitrogen oxides and carbon and smoke particles in a certain temperature.

THE NUMERICAL SIMULATION METHOD OF EXHAUST FLOW IN CMWF FILTER

Porous medium, pure fluid coupling flow area, could be formed when the diesel exhaust flows through the DPF filter. For these kind problems of coupling area flow, the traditional numerical simulation mainly has two methods: the first one is the numerical simulation method which uses Darcy or Forchheimer equation and slip boundary condition (Beavers and Joseph, 1967); the second one is the numerical simulation method which uses Brinkman equation or Brinkman-Forchheimer equation (Beavers and Joseph, 1967). Due to the diesel engine exhaust has high emission rate and great pressure, the steady non Darcy flow by using the compressible gas through the porous media was used to take a flow analysis, the flow diagram as shown in Fig. 2. In the figure, p_1 , ρ_1 and v_1 are pressure, density and speed of exhaust before the DPF filtration device whose x axis length is H , p_0 , ρ_0 and v_0 are ones of exhaust after the DPF. Because of the exhaust would be released into the atmosphere from the DPF directly, the

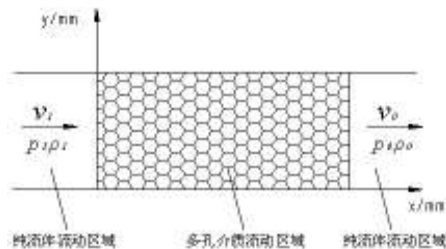


Fig. 2: Flow diagram of diesel engine exhaust gas flowing through DPF

value of p_0 equals approximate standard atmospheric pressure, $p_0 = 1.013 \times 10^5$ Pa.

In order to establish the mathematical model of exhaust flow in CMWF DPF, the study make the following assumptions about the flow analysis: Flow steady non-Darcy flow which meet the Darcy-Forchheimer law; the fluid temperature T is constant, when Klinkenberg effect is ignored; the porous medium is rigid porous medium.

Considering the motion equation (Darcy-Forchheimer equation) corrected by Forchheimer is:

$$\frac{dp}{dx} = -\frac{\mu}{k}v - \beta\rho v^2 \quad (1)$$

where,

p = The gas pressure expressed in Pa

v = The flow rate expressed in m/s

ρ = The gas density expressed in kg/m^3

μ = The viscosity coefficient

β = The inertial coefficient

Because in the particular container, the high speed flow of the exhaust meets mass conservation equation, the relationship between mass average flow and cross-sectional area of the filter meets the following equation (Zuo, 2007):

$$\rho S v = Q_m \quad (2)$$

where,

S = The cross-sectional area expressed in m^2

Q_m = The mass average flow expressed in kg/s

The state equation is:

$$p = \rho RT \quad (3)$$

where,

p = The absolute gas pressure expressed in N/m^2

R = The gas constant, the value of dryair is $287.1 \text{ N}\cdot\text{m}/(\text{kg}\cdot\text{K})$

T = The air thermodynamic temperature expressed K

With reference to Eq. (2) and (3):

$$v = \frac{Q_m}{\rho S} = \frac{Q_m}{S} \frac{RT}{p} = \frac{Q_m RT}{S p} \quad (4)$$

Substituted in Eq. (1):

$$\frac{dp}{dx} = -\frac{Q_m RT}{S} \left[\frac{\mu}{k} + \frac{Q_m}{S} \beta \right] \frac{1}{p} \quad (5)$$

And

$$b = \frac{Q_m RT}{S} \left[\frac{\mu}{k} + \frac{Q_m}{S} \beta \right] = p_1 v_1 \left[\frac{\mu}{k} + \frac{Q_m}{S} \beta \right] = p_1 v_1 \left[\frac{\mu}{k} + \rho_1 v_1 \beta \right] \quad (6)$$

Because the exhaust flows in CMWF DPF steady flow given by straight pipe inlet parameters, Q_m is a constant. For rigid porous media, k and β are all constants. For the gas isothermal flow, T and μ are all constants:

$$\frac{dp}{dx} = -b \frac{1}{p} \quad (7)$$

The equation above is flow pressure equation, which could be integrated:

$$\frac{1}{2} p^2 = -bx + c \quad (8)$$

$x = 0$ and $p = p_1$, the boundary condition, was substituted to determine the integration constant: $c = \frac{1}{2} p_1^2$, which substituted in Eq. (8):

$$p^2 = p_1^2 - 2bx \quad (9)$$

$$p = \sqrt{p_1^2 - 2bx} = p_1 \sqrt{1 - \frac{2b}{p_1^2} x} \quad (10)$$

The equation above is the flow pressure distribution. Formula (4) shows that:

$$pv = p_1 v_1 = p_0 v_0 = \frac{Q_m RT}{S} \quad (11)$$

So the velocity distribution of the gas in the porous medium can be obtained as follow:

$$v = \frac{p_1 v_1}{p} = \frac{v_1}{\sqrt{1 - \frac{2b}{p_1^2} x}} \quad (12)$$

According to formula (9) and (6), when $x = H$, $p = p_0$, the follows could be known as:

$$p_0^2 = p_1^2 - 2p_1 v_1 \left[\frac{\mu}{k} + \frac{p_1}{RT} v_1 \beta \right] H \quad (13)$$

Finishing could be obtained:

$$\frac{\mu}{k} + \frac{p_1}{RT} v_1 \beta = \frac{p_1^2 - p_0^2}{2H p_1 v_1} \quad (14)$$

For the condition of that the gas pressure is p_2 , velocity is v_2 before the porous medium:

$$\frac{\mu}{k} + \frac{p_2}{RT} v_2 \beta = \frac{p_2^2 - p_0^2}{2H p_2 v_2} \quad (15)$$

Simultaneous (14) and (15):

$$\beta = \frac{RT}{2H(p_1 v_1 - p_2 v_2)} \left[\frac{p_1 - p_2}{v_1 - v_2} + p_0^2 \left(\frac{1}{p_2 v_2} - \frac{1}{p_1 v_1} \right) \right] \quad (16)$$

$$\frac{\mu}{k} = \frac{p_1^2 - p_0^2}{2H p_1 v_1} - \frac{p_1 v_1}{2H(p_1 v_1 - p_2 v_2)} \left[\frac{p_1 - p_2}{v_1 - v_2} + p_0^2 \left(\frac{1}{p_2 v_2} - \frac{1}{p_1 v_1} \right) \right] \quad (17)$$

In the research on flow characteristics of exhaust in the CMWF DPF, the relationship of $\Delta p/H$ (the ratio of pressure difference to the length of DPF filter) with the exhaust flow rate v_1 is very important. According to it the relationship of pressure difference with exhaust flow could be obtained easily. By using above formulas, the analytical expression of the relationship of $\Delta p/H$ and v_1 which suitable for the compressible gas can be obtained.

According to the formula (9) and (6):

$$p_0^2 = \left(1 - \frac{2H\beta v_1^2}{RT} \right) p_1^2 - 2H \frac{\mu}{k} p_1 v_1 \quad (18)$$

Formula (18) is quadratic equation with variable p_1 , solve the equation:

$$p_1 = \frac{-2H \frac{\mu}{k} v_1 \pm \sqrt{\left(2H \frac{\mu}{k} v_1 \right)^2 - 4p_0^2 \left(\frac{2H\beta v_1^2}{RT} - 1 \right)}}{2 \left(\frac{2H\beta v_1^2}{RT} - 1 \right)} \quad (19)$$

According to formula (13):

$$2 \frac{p_1^2 v_1^2}{RT} H \beta < 2 p_1 v_1 \left(\frac{\mu}{k} + \frac{p_1 v_1}{RT} \beta \right) H = p_1^2 - p_0^2 < p_1^2 \quad (20)$$

can be adopted as basis of contrast enhancement methods. So, $\frac{2H\beta v_1^2}{RT} < 1$, the reasonable solution of formula (18):

$$p_1 = \frac{-2H \frac{\mu}{k} v_1 - \sqrt{\left(2H \frac{\mu}{k} v_1 \right)^2 - 4p_0^2 \left(\frac{2H\beta v_1^2}{RT} - 1 \right)}}{2 \left(\frac{2H\beta v_1^2}{RT} - 1 \right)} \quad (21)$$

Formula (21) shows the relationship of the pressure before CMWF DPF with flow velocity. Then the relationship of $\Delta p/H$ and v_1 could be obtained:

$$\frac{\Delta p}{H} = \frac{p_1 - p_0}{H} = \left(\frac{-2H \frac{\mu}{k} v_1 - \sqrt{\left(2H \frac{\mu}{k} v_1\right)^2 - 4p_0^2 \left(\frac{2H\beta v_1^2}{RT} - 1\right)}}{2\left(\frac{2H\beta v_1^2}{RT} - 1\right)} - p_0 \right) / H \quad (22)$$

The simulation experiment of the flow characteristics of CMWF DPF: The method to study the flow characteristics of CMWF filter material by using diesel engine bench test has high fuel consumption, long test cycle, the different effect factors for exhaust flow characteristics caused by the model and running condition of engine and particle deposition. So the results of bench test have some certain limitations. In order to measure the exhaust flow characteristic in CMWF DPF accurately and economically, the measurement device for exhaust flow characteristic in CMWF DPF is designed.

The test instrument mainly includes: LGU22A fixed twin-screw air compressor with 3.8 m³/min maximum displacement and 0.7 M maximum working pressure; the air reservoir with the heating system; TF turbine flow sensor, with 0.7 M maximum pressure and ±3% FS measurement accuracy; HJ69-JPG3 pressure sensor with 0~350 kPa~70 MPa measuring range; PT100 temperature sensor; self-development detachable DPF, whose photograph is shown in Fig. 3. The length of intermediate pipe selectable mainly includes 50, 100, 150 and 200 mm, respectively.

In the test, three kinds of CMWF filter with different apertures include crude holes, holes and pores (respectively marked as filter (I, II, III) were studied. These filters are all, in clean state, whose cross-sectional area and length are all 1.539×10⁻² m² and 100 mm respectively. The mainly parameters of CMWF filter are shown in Table 1.

In order to obtain the average temperature of the airflow in CMWF DPF, the American Raiterrayteck non-contact infrared thermometer was apply to measure the actual exhaust temperatures of 205 diesel vehicles driven into Harbin at Harbin highway toll stations, which measuring position is DPF installation position, the tail pipe. By averaging the test results, we could obtain that the average temperature at tail pipe T is 367.39 K, corresponding gas dynamic viscosity coefficient $\mu = 2.43 \times 10^{-5}$ kg/m.s. By using the exhaust flow characteristic measure device for CMWF DPF, we could control the temperature of the airflow, change the pressure and flow of the airflow in front of the filter, simulate the flow characteristics of diesel engine exhaust and also measure a series of pressure and velocity in front of the filter. The data about filter I are shown in Table 2; the ones about II and III are omitted here.

Table 1: Major parameters of CMWF filters

	Crude holes CMWF I	Holes CMWF II	Pores CMWF III
Average size of pores	0.83	0.45	0.06
Porosity	87	86	87

Table 2: Results of simulation experiment for flow characteristics in CMWF DPF

No.	Velocity (m/s)	Pressure (105 Pa)	No. 1	Velocity (m/s)	Pressure (105 Pa)
1	2.10	1.0368	2	2.49	1.0369
3	3.39	1.0370	4	4.29	1.0373
5	5.12	1.0376	6	5.87	1.0381
7	6.17	1.0386	8	7.09	1.0389
9	7.16	1.0496	10	7.36	1.0580
11	7.50	1.0638	12	8.15	1.0740
13	8.34	1.0858	14	9.18	1.0978
15	9.38	1.1478	16	9.67	1.1591



Fig. 3: Photograph of a detachable DPF

SIMULATION AND EXPERIMENTAL RESULT ANALYSIS

Combined with known conditions, one of the total 16 sets of data was banded together with any other one of all and the penetration and inertia coefficient could be calculated by using formula (15) and (16), then by omitting unreasonable results and averaging the remaining ones, the penetration and inertia coefficient of filter I could be obtained: $k = 3.000 \times 10^{-8}$ m²; $\beta = 701.1$ m⁻¹. The ones of filter II and III could be obtained by using the above method. Substituting the permeabilities and inertia coefficients of filter I, II and III into formula, respectively, three parabolas could be obtained. By drawing the coordinate points of $\Delta p/H$ (Δp is the pressure difference of the values detected by two pressure sensors) and v_1 and the three parabolas into the same coordinate system, the relationship of $\Delta p/H$ and v_1 of CMWF DPF could be obtained, which was shown in Fig. 4.

Figure 4 shows that the experimental results agree with theoretical ones excellently, so the numerical simulation method is feasible. When the porosities of the filters are similar, the smaller the average pore size is, the longer the focal of the parabola, which means the faster the increasing speed of filter resistance for exhaust flow with the increase of exhaust flow velocity. According to the references (Ma *et al.*, 2009; Neale and Nader, 1974; Hua and Yang, 1985), the total remove efficiency of DPF for soot is inversely proportional to

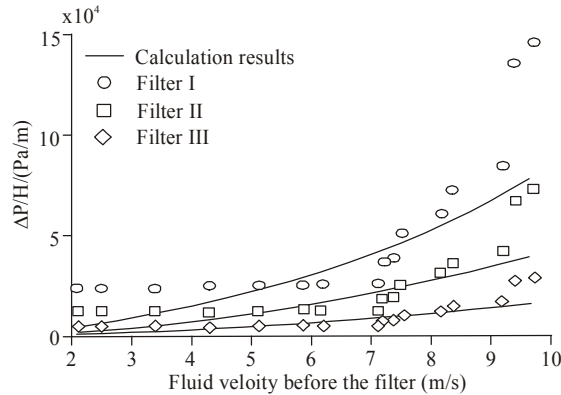


Fig. 4: Relation between $\Delta p/H$ and $s v_1$ of CMWF DPF

pore diameter; the pressure in filter and filtration efficiency are all proportional to the length of filter. So the determine of pore diameter is a very important factor which could keep the balance of filtration efficiency and exhaust resistance when we design a CMWF DPF. In the permission of vehicle chassis structure, the filter media with longer length and bigger pore diameter is sure to win out over ones with shorter length and smaller pore diameter, which could keep smaller resistance in filter under the same filtration efficiency.

CONCLUSION

- In this study, CMWF was used in the purification of the diesel exhaust. According to the characteristic of higher pressure and velocity when exhaust flow through the filter, the steady non Darcy flow by using the compressible gas through the porous media was used to take an flow analysis for CMWF DPF and the permeability, inertia coefficient and the geometric relationship of $\Delta p/H$ (the ratio of pressure difference to the length of DPF filter) with v_1 (the exhaust flow rate in front of filter). The test shows that the results detected by the self-developed CMWF flow characteristic simulation test-bed are agree with theoretical results greatly, which shows the numerical simulation method is feasible.
- The determination of the pore diameter is a very important factor. Theory and practice show that, in the permission of vehicle chassis structure, the filter media with longer length and bigger pore diameter is sure to win out over ones with shorter length and smaller pore diameter, which could keep smaller resistance in filter under the same filtration efficiency.

ACKNOWLEDGMENT

This study is supported by Fundamental Research Funds for the Central Universities (DL11CB01), China Postdoctoral Science Foundation (20100471013) and

Project of Driven to Green of China Environmental Protection Foundation.

REFERENCES

- Adler, J., 2005. Ceramic diesel particulate filters. *Int. J. Appl. Ceram. Tec.*, 2: 429-439.
- Beavers, G.S. and D.D. Joseph, 1967. Boundary conditions at a naturally permeable wall [J]. *J. Fluid Mech.*, 30: 197-207.
- Fang, H., J. Wang and K. Liu, 2009. Thinking on the strategy of energy saving and emission reduction for China's automotive industry [J]. *Auto Ind. Res.*, 8: 2-6.
- He, H., D. Weng and X. Zi, 2007. Diesel emission control technologies: A Review [J]. *Environ. Sci.*, 6: 1169-1176.
- Hua, S. and X. Yang, 1985. *The Practical Fluid Resistance Manual* [M]. National Defense Industry Press, Beijing, pp: 141-267.
- ISO4022, 1977. Permeable Sintered Metal Materials-determination of Fluid Permeability [S]. Retrieved from: <http://www.scc.ca/en/search/standardsdb?Page=8644>.
- Juan, Y., S. Mark and M. Gary, 2009. Single wall Diesel Particulate Filter (DPF) filtration efficiency studies using laboratory generated particles. *Chem. Eng. Sci.*, 64(1): 1625-1634.
- Kaviany, M., 1991. *Principles of Heat Transfer in Porous Media* [M]. Springer-Verlag, New York.
- Li, Q., Y. Xie, Y. Zhong and W. Zhu, 2009. Research progress in technologies for the abatement of soot particles from engines [J]. *J. Zhejiang Norm. Univ. Nat. Sci.*, 3: 97-102.
- Ma, Y., 2001. Prospect nanometer and micrometer science and technology for applying to the wood industry [J]. *ScientiaSilvaeSinicae*, 6: 109-113.
- Ma, Y., H. Ren and X. Zhang, 2003. The research on cleaved theory by using micron compression to recombine high molecular orientation materials. *Proceeding of Conference on Advanced Manufacturing Technology, System and Equipment*, 12: 316-318.
- Ma, Y., X.R. Guo, F.H. Wang and D.F. Du, 2009. Pressure drop gradient of carbonized Micro-length wood fiber DPF [J]. *ScientiaSilvaeSinicae*, 45(12): 118-123.
- Neale, G. and W. Nader, 1974. Practical signification of Brinkman's extension of Darcy's law: Coupled parallel flows within a channel and a bounding porous medium [J]. *Canada J. Chem. Eng.*, 52: 475-478.
- Wang, P., X. Guo, Y. Ma and D. Du, 2010. Present status and development trend of the exhaust particulate filter for diesel vehicles [J]. *Small Int. Combust. Engine Motorcycle*, 39: 91-96.
- Zuo, J., 2007. *Hydraulic and Pneumatic Drive* [M]. China Machine Press, Beijing, pp: 205-206.