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Study on test instrument and filtration theory of the carbonized micron wood fiber DPF

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ABSTRACT

In this paper, a method of utilizing the carbonized micron wood fiber (CMWF) as the filter material is presented and a corresponding numerical simulation method is applied. Furthermore, a kind of detachable diesel particulate filters (DPF) is developed, a diesel engine bench test is conducted and the influence elements upon $\Delta p/H$ are researched. Theory and test show that the smaller the average micro pore diameter is, the larger the focal length of parabola is, which means that the numerical simulation method can be consistent with the test very well. Meanwhile, a lot of tests prove that the DPF filters with bigger pore diameter and longer length should take priority over the others, together with the increase of the filter length, the PM arresting efficiency will be improved and $\Delta p/H$ also climbs up rapidly and a kind of modified CMWF DPF, of which the micro pore diameter reduces gradually from entry to exit end, possesses high filtration efficiency and low pressure drop and be suited to filter the exhaust gases of diesel.

1. Introduction

Airborne particulate matter is known for its environmental impact [1,2] and is suspected of causing adverse health effects [3,4]. Especially the role of ultrafine particles smaller than 0.1 μm, which amongst others are emitted by diesel engines, is the subject of current health related discussions [5,6].

Against this background the legal PM (particulate material) emission limits for diesel vehicles continue to be tightened throughout the world (e.g. EU-5 Regulation of the European Parliament). Driven by these regulatory changes and the increasing customer demand for environment friendly vehicles which are capable of complying with future regulations, the implementation of diesel particulate filters (DPF) seems to be essential [7]. An excellent DPF should have high filtration efficiency and low flow resistance, and should be able to withstand the high temperatures. Several porous materials such as cordierite, silicon carbide (SiC), active carbon fiber, etc. have been explored for use in DPF, with cordierite and SiC being the two most commonly used at present [8]. However, almost no kind of purification method is entirely satisfactory [9,10]. In this paper, a method of utilizing the carbonized micron wood fiber (CMWF) as the filter material is presented and a corresponding numerical simulation method is applied. Furthermore, a kind of detachable DPF is developed, a diesel engine bench test is conducted and the influence elements upon $\Delta p/H$ (ratio of the pressure difference before and after the DPF filter and the filter length) are researched. Theory and test prove that the numerical simulation method can be consistent with the test very well and the CMWF DPF has not only the low flow resistance and high efficient filtration but also very suitable for diesel exhaust gas purification.

2. Material and methods

2.1. Materials

Micron wood fiber (MWF) can be formed by processing high-strength wood fiber to micron-thickness. If such MWF and other materials are mixed with appropriate ratio and carbonized through special techniques, carbonized micron wood fiber (CMWF) could be achieved. MWF and CMWF DPF filter are showed in Fig. 1. In the course of the study on nano-micron processing technology, micron fiber recombination can change the arrangement of wood structure completely, which can successfully increase its strength and eliminate its natural flaw [11]. The CMWF achieved by processing this kind of recombination wood fiber possesses not only high porosity, large specific area, fast velocity of adsorption and big adsorption capacity, but also different active functional group with function of catalytic conversion for exhaust gas, which can reduce nitric oxide and soot in emissions simultaneously. In addition, compared with DPF used commonly at present, CMWF DPF has the characteristics of environmental protection, anti-corrosion, strong ability of catching soot and low price. If the function of adsorption

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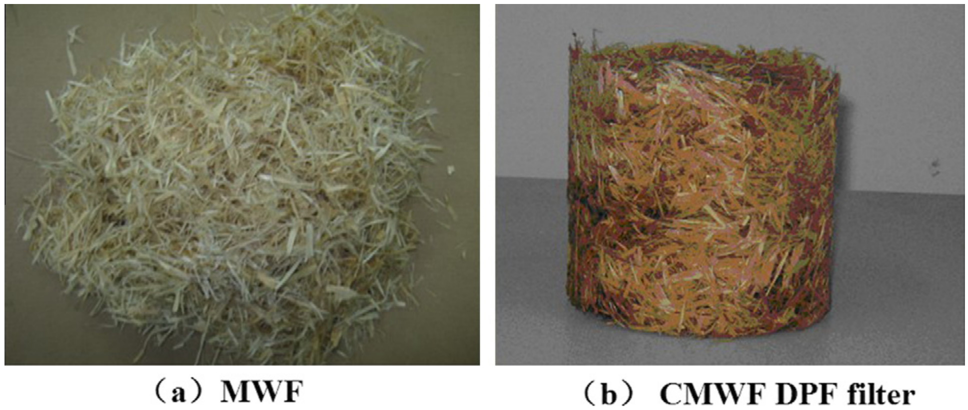

Fig. 1. MWF and CMWF DPF filter.

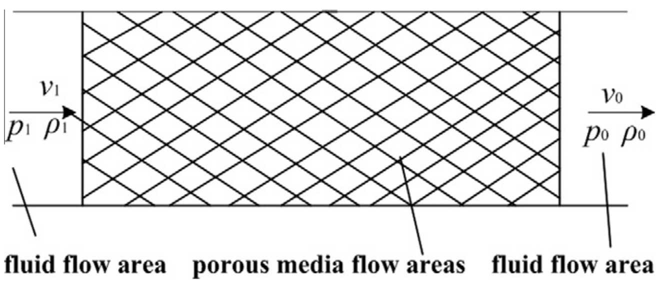

Fig. 2. Flow diagram of diesel engine exhaust gas flowing through the DPF.

and noise reduction of CMWF were applied to filter the exhaust gas of diesel engine, we could pioneer a new direction in the research with large scientific and economic value.

2.2. Methods

2.2.1. The numerical simulation for exhaust flow in CMWF DPF

The permeability and inertia coefficient are two very important parameters concerned with fluid flow characteristics in porous media [12,13]. Therefore, the accurate determination of the permeability and inertia coefficient is very crucial for the study of porous media. When exhaust gas of diesel engine flows through the DPF filter, the porous media – fluid coupled areas can be formed, in which the traditional numerical simulation methods are mainly two categories for the flow problem: the method using Darcy or Forchheimer equation with slippage boundary condition [14] and the method using Brinkman or Brinkman–Forchheimer equation [15]. Because of the high exhaust emission speed and pressure of the diesel engine, the analysis of non-Darcy steady compressible gas flow in porous media is applied in this paper. The flow diagram is shown in Fig. 2, where p_1, ρ_1, v_1 and p_0, ρ_0, v_0 are, respectively, the pressure, density and speed before and after the exhaust gas flow through the DPF filter, H is the length of the DPF filter, and the ρ_0 approximates the standard atmospheric pressure due to the gas discharged into the atmosphere directly.

In order to establish mathematical model consistent with the flow behaviors of exhaust gas in CMWF DPF filter, the assumptions are made as follows: steady flow; non-Darcy flow that meets the requirements of Darcy–Forchheimer equation; ignoring Klinkenberg effect; porous medium is rigid; viscosity coefficient μ, fluid temperature T, permeability k and inertial coefficient β are all constants.

Darcy–Forchheimer equation is:

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

where p is the gas pressure, v is the flow velocity, ρ is the gas density.

Mass conservation equation is:

$$\rho S v = Q_m \tag{2}$$

where S is the cross-sectional area of the filter. Q_m is the mass flow.

Equation of state is:

$$p = \rho R T \tag{3}$$

According to Eqs. (2) and (3), we can get:

$$v = \frac{Q_m}{\rho S} = \frac{Q_m}{S}\frac{RT}{p} = \frac{Q_m RT}{S}\frac{1}{p} \tag{4}$$

According to Eqs. (4) and (1), the Eq. (5)can be obtained as:

$$\frac{dp}{dx} = -\frac{Q_m RT}{S}\left[\frac{\mu}{k} + \frac{Q_m}{S}\beta\right]\frac{1}{p} = -p_1 v_1 \left[\frac{\mu}{k} + \frac{Q_m}{S}\beta\right]\frac{1}{p} = -p_1 v_1 \left[\frac{\mu}{k} + \rho_1 v_1 \beta\right]\frac{1}{p} \tag{5}$$

As the exhaust flow in the CMWF DPF belongs to steady flow with given straight pipe entrance parameters, Q_m is a constant. For rigid porous medium, k and β are constants. Meanwhile, T and μ are also constants due to the isothermal gas flow. By Eq. (5) we can see, $p_1 v_1 \left[\frac{\mu}{k} + \rho_1 v_1 \beta\right]$ is a constant.

Namely, the Eq. (5) is the gas flow pressure equation, the integral result of which is:

$$\frac{1}{2}p^2 = -p_1 v_1 \left[\frac{\mu}{k} + \rho_1 v_1 \beta\right]x + c \tag{6}$$

Substituting the boundary conditions of $x = 0$, $p = p_1$ into Eq. (6), the integral constant $c = \frac{1}{2}p_1^2$ can be determined. The Eq. (7) can be obtained by substituting integral constant into Eq. (6)

$$p^2 = p_1^2 - 2p_1 v_1 \left[\frac{\mu}{k} + \rho_1 v_1 \beta\right]x \tag{7}$$

$$p = \sqrt{p_1^2 - 2p_1 v_1 \left[\frac{\mu}{k} + \rho_1 v_1 \beta\right]x} = p_1 \sqrt{1 - \frac{2p_1 v_1 \left[\frac{\mu}{k} + \rho_1 v_1 \beta\right]}{p_1^2}x} \tag{8}$$

Eq. (8) is the flow pressure distribution. The following equation can be got according to Eq. (4).

$$p v = p_1 v_1 = p_0 v_0 = \frac{Q_m RT}{S} \tag{9}$$

The velocity distribution of gas in porous media can be obtained: