Universiti Malaysia PAHANG

JILID VOLUME 02 ISSN 1985-5176 DISEMBER DECEMBER 2009

# JURNAL UMP

## KEJURUTERAAN DAN SAINS KOMPUTER
## *ENGINEERING AND COMPUTER SCIENCE*



UNIVERSITI MALAYSIA PAHANG

# Three-Dimensional CFD study of a Candle Ceramic Filter

Jolius Gimbun*[1], Ili Izyan Safuraa Abdul Karim[1], Luqman Chuah Abdullah[2]

## ABSTRACT

*Tightened environmental legislation enacted as a consequence of government policy has compelled industry to pay serious attention to air pollution issues. Gas cleaning with ceramic filters has proven to be the most important technology for removal of particulate emissions at high temperatures. This paper presents a computational fluid dynamics (CFD) investigation of a rigid candle ceramic filter. The aim is to examine numerically the pressure drop and velocity profile along the candle filter under a filtration mode. The filter element was modeled as a porous medium and the media resistance at x, y and z direction is assumed to be isotropic. The gas flow within the porous media (filter element) is also assumed to be a laminar flow. The CFD calculations show a good agreement with the experimental data, with an average discrepancy around 5%, which probably in the same magnitude of the experimental error. The modeling exercise presented in this study offers an alternative solution for examining a pressure drop in ceramic filter via computational method and may be useful in design of a ceramic filter.*

Keywords: Ceramic filter, candle filter, CFD, pressure drop, velocity profile

## 1. Introduction

Many industrial processes involve the generation of hot waste gases, which can be contaminated with solid, liquid or gaseous pollutants. In certain application such as the power generation plant a particle free hot gas is desired because particles from the combustion gases may erode the turbine blades and hence reduce efficiency. Therefore, it is necessary to filter the combustion gasses in order to reduce the particulate to a satisfactory level both in terms of emissions standard and turbine wear. Meanwhile, in the chemical and process industries and in incineration, the need for gas cleaning is being driven increasingly by the environmental legislation. Government policy has compelled industry to pay serious attention to air pollution issues. This has resulted in the need to install air pollution control equipment.

Conventional hot gas technology such as cyclones, electrostatic precipitators and wet scrubbers is becoming less attractive with the tightening of emission limits. Furthermore, the filtration requirements at high pressure and high temperature have stimulated the development of new technology. The reasons for cleaning gases hot rather than cold are many and various. They include the need to remain well above acid dew points, improved thermodynamic efficiency, especially where downstream heat recovery is employed and an improvement in the versatility of the overall process. In cases where the alternative is to cool process gases by dilution with ambient air, there may also be simple economic advantages to filtering the gases hot. Of the available cleaning methods, the rigid ceramic filter has proven to be an effective gas filtration device for uses at high temperature (Seville *et al*., 1989; Seville, 1997; Seville *et al.*, 2003). A rigid ceramic filter can withstand temperatures up to 1300 K or even higher (Chuah *et al.,* 1999).

An accurate prediction of pressure drop across the filter media is important because it relates directly to the power required to operate the filter. A filter with higher throughput is always desired, and it can be achieved simply by increasing the average filter face velocity. However, pressure drop increase proportionally with the average face velocity hence a trade off must be made between the operating costs and filter throughput.

Earlier, ceramic filter modeling was made via specific purpose code like PARTICULATE of Ahmadi and coworkers (Li *et al.*, 1994; He and Ahmadi, 1999) and many other FORTRANs or MS Excel based code like the one-dimensional model of Chuah *et al.* (2004) and Ito *et al.* (1998). Chuah *et al.* (1999; 2004) has employed one-dimensional model and two-dimensional CFD simulation to model the candle filter. They managed to obtain a reasonable prediction on pressure drop distribution however no comparison were made on velocity profile along the filter length.

Aroussi *et al.* (2001) also studied the particle deposition on a single ceramic filter via CFD. They compared their simulation result against particle image velocimetry (PIV) measurement. They reported a largely under prediction of particle deposition along the filter length. Ahmadi and Smith (2002) studied a filter vessel with a single filter arrangement. They presented a theoretical particle trajectory inside the filter vessel however no comparison made on the velocity and pressure drop profile along the filter. Later they studied a real filter vessel with multiple filter arrangement (Gamwo *et al*., 2002). Gamwo et al.'s has presented a pressure and velocity profile however no comparison made with actual experimental measurement. Al-Hajeri *et al.* (2005) employed a CFD to model the flow passing a candle filter. They reported a reasonably good agreement between the CFD prediction and their PIV measurement on the particle convergence around the single candle filter. Recently, Tanthapanichakoon *et al.* (2008) published a CFD study on a filter vessel fitted with two candle filter, and they reported a good agreement between CFD prediction and measured total pressure drop. Of all the previous CFD studies on ceramic filter, none has published the prediction of pressure drop and velocity profile along the filter length. It is important to study these parameters along the filter length because they have a great influence on the cake formation and detachment from the filter media. As reported by Kanaoka and Amornkitbamrung (2001) a uniform pressure and velocity profile along the candle filter length is necessary for a better cake detachment from candle ceramic filter. The major advantage of CFD lies on it ability to provide an unimaginable amount of data ranged from hydrodynamics, reaction, mixing, separation, heat and mass transfer, shear and stress and many others. Thus, CFD could play an important role in designing a filter with more uniform pressure drop and velocity distribution. This study attempts to reproduce numerically the pressure drop and velocity profile along the candle filter. The CFD prediction is compared to the experimental measurement from Chuah (2000).

A rigid candle ceramic filter as illustrated in Fig. 1 which has been evaluated experimentally by Chuah (2000) is considered in this work. The candle filter has a length of 1 m and the thickness of the filter media is 0.01 m. The filter is vacuum-formed on the outside of a permeable tool from slurry of $Al_2O_3$ and SiO fibres, water and a mixture of organic and inorganic binders (Seville *et al.*, 1989).

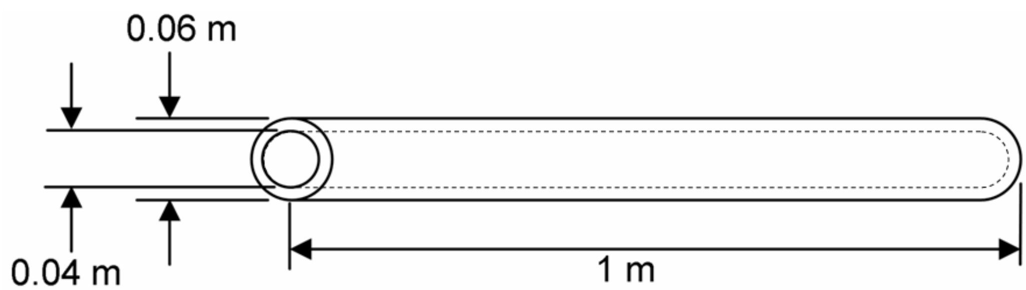


Fig. 1: Dimension of candle ceramic filter

## 2. CFD Approach

Mathematical modeling of the flow in a full size three-dimensional filter element was performed using a commercially available general purpose CFD code, FLUENT 6.1. The internal flow dynamics and pressure drop in the filter element are determined via the solution of conservation equations. A finite volume technique is employed to ensure that all solutions satisfy the conservation equations and provide solution stability and accuracy. The candle ceramic filter was represented using a full scale tetrahedral mesh that consisted of 1935 nodes as shown in Fig. 2. A velocity inlet boundary was used to specify the filter surface ranged from 4 to 6 cm/s. An outflow boundary condition was used to represent the filter open end. The filter element was modeled via porous media model available in FLUENT. The porous media are modeled by additional momentum sources term to the standard fluid flow equations. The source term is composed of two parts, a viscous loss term (Darcy), and an inertial loss term. This is the anisotropic vectorised Ergun equation:

$$S_i = \sum_{j=1}^{3} D_{ij}\mu \underline{u}_j + \sum_{j=1}^{3} C_{ij}\frac{1}{2}\rho\left|\underline{u}_j\right|\underline{u}_j \qquad (1)$$

where $S_i$ is the source term for the $i^{th}$ (x, y, z) momentum equation, and $D$ and $C$ are prescribed matrices. The momentum sink contributes to pressure gradient in porous cell, creating a pressure drop that is proportional to fluid viscosity and momentum in the cell. Assuming a simple isotropic, homogeneous porous media, equation (1) can be rewritten as:

$$S_i = \frac{\mu}{\alpha}\underline{u}_i + C_2 \frac{1}{2}\rho|\underline{u}_i|\underline{u}_i \qquad (2)$$

where $\alpha$ is the permeability and $C_2$ is the inertial resistance factor. In laminar flows through porous media, the pressure drop is typically proportional to viscosity and the constant $C_2$ can be considered to be zero. Ignoring convective acceleration and diffusion, the porous media model then reduces to Darcy's Law:

$$\nabla P = -\frac{\mu}{\alpha}\underline{u} \qquad (3)$$

The permeability value, $\alpha$ = 6.3 x$10^{-12}$ $m^2/s$ is adopted from the experimental work of Chuah (2000). The finite volume methods have been used to discretised the partial differential equations of the model using the SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) method for pressure-velocity coupling and the second order scheme to interpolate the variables on the surface of the control volume. The segregated solution algorithm was selected and the laminar model was also applied in the porous region.

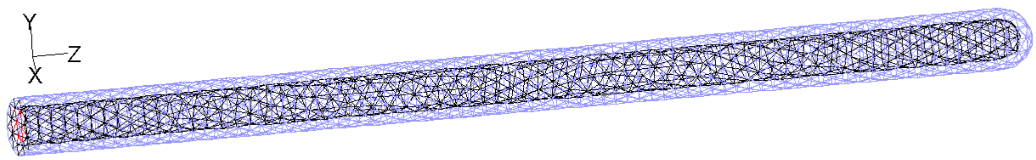


Fig. 2: The CFD computational mesh of the ceramic filter

Table 2: Parameters used in the simulations

| | |
|---|---|
| Length of candle | 1.00 m |
| Outside diameter, O.D. | 0.06 m |
| Inside diameter, I.D. | 0.04 m |
| Density of air, $\rho_{air}$ | 1.225 $kg/m^3$ |
| Permeability, $\alpha_{filter}$ | 6.3 x$10^{-12}$ $m^2/s$ |

## 3. Result and Discussion

Chuah (2000) has performed a detail measurement of pressure drop and velocity profile along the filter candle varying the face velocity from 4 cm/s to 6 cm/s. Aware of the availability of Chuah's experimental data for validation, the CFD simulation was also performed at the same face velocity. Fig. 3 shows the contour of velocity magnitude along the center region of the filter candle. The velocity magnitude at the hollow region of the filter shows an increasing trend as it moving toward the open end where the pump is situated in the actual experiment. The highest velocity magnitude can be spotted at the filter center region near the open end. This higher velocity created a lower local static pressure which inevitably lead into a higher pressure drop in this region. The contour of the static pressure along the center region of the filter candle in Fig. 4 clearly shows the evidence of a lower static pressure at the open end of the filter candle.

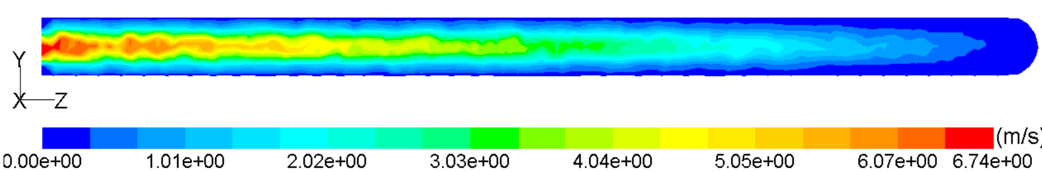


Fig. 3: Contour map of velocity magnitude at the centre region of the filter

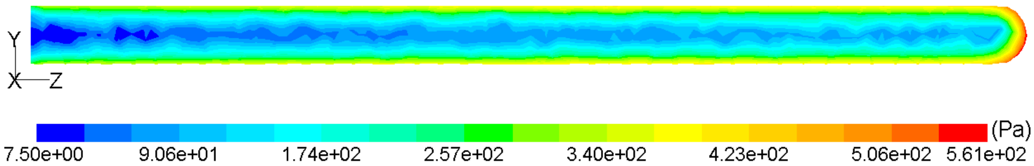


Fig. 4: Contour map of static pressure at the centre region of the filter

The pressure drop of ceramic filter was calculated by obtaining the differences between static pressure at filter center axis and also static pressure at the surface of filter model. Figs. 5, 6 and 7 show the calculated pressure drop at various mean surface velocities were compared with experimental data from Chuah (2000). The CFD prediction is in good agreement with the experimental data of Chuah (2000) within about 5% average error, which might be in the same range to the experimental error. The assumption of an isotropic flow resistant for the porous zone modeling is suspected to have attributed the error. It is safe to assume an isotropic media resistant on x and y direction where the internal velocity did not differ appreciably, but the same may not be true in z direction. In this study, the media resistant acting on z direction is calculated by taking into considering the average internal z velocity hence it represents the average value rather than the local ones. Consequently, this assumption lead into a little overprediction on the pressure drop profile. Nevertheles, the effect of the media resistant on z direction is minimal considering the fact that most of the gas flowing through the filter element (porous media) in x and y direction. For that reason, the CFD prediction were in close agreement with the experimental measurement despite using the isotropic media resistant assumption.

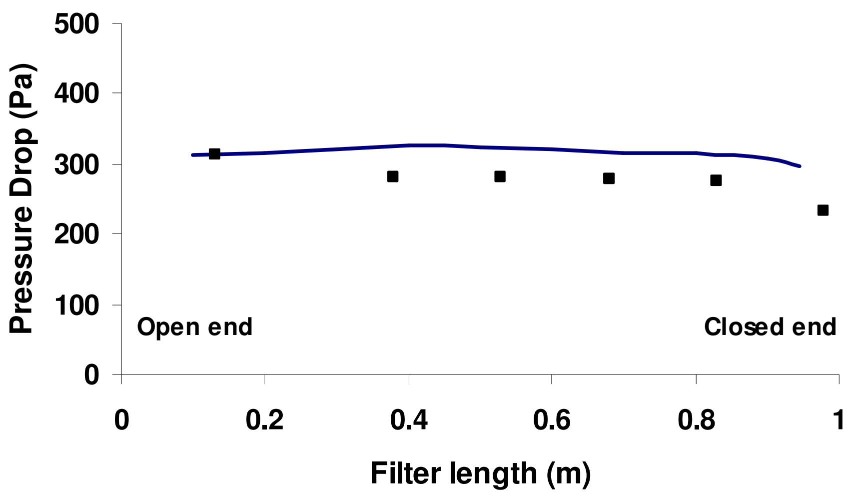


Fig. 5: Prediction of pressure drop along the filter length at face velocity 4 cm/s. Data points is adopted from Chuah (2000).

The commonly observed phenomenon of pressure drop increased proportionally with advancing of face velocities is also reproduced correctly by the CFD simulation. These increase are attributed by the fact that the media resistance in Darcy's law increases proportionally with the square of face velocity. It should also be noted that the pressure drop at the open end is slightly higher compared to the pressure drop the closed end. These trends of an increasing pressure drop toward the open end of the filter candle are attributed by the increases in the velocity magnitude inside the hollow region of the filter. The rise in velocity magnitude towards the open end of the filter is attributed by the continuous flow of gas moving through the filter media along the filter candle. Comparison between the calculated and measured velocity profile along the candle center region is shown in Fig. 8. The CFD prediction shows a fair agreement with Chuah (2000) experimental data. The trend of higher velocity at the open end of the filter has also been successfully elucidated numerically. These increasing velocity trend as mentioned earlier is associated with the constant inflow of gas along the filter length.

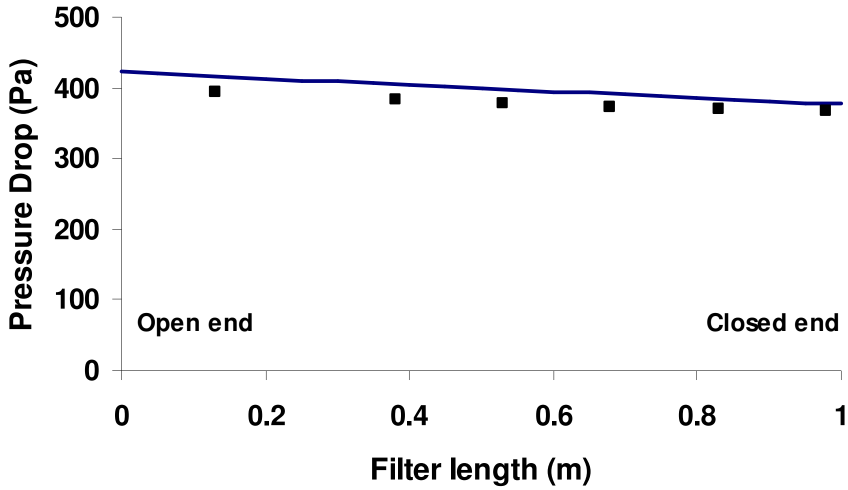


Fig. 6: Prediction of pressure drop along the filter length at face velocity 5 cm/s. Data points is adopted from Chuah (2000).

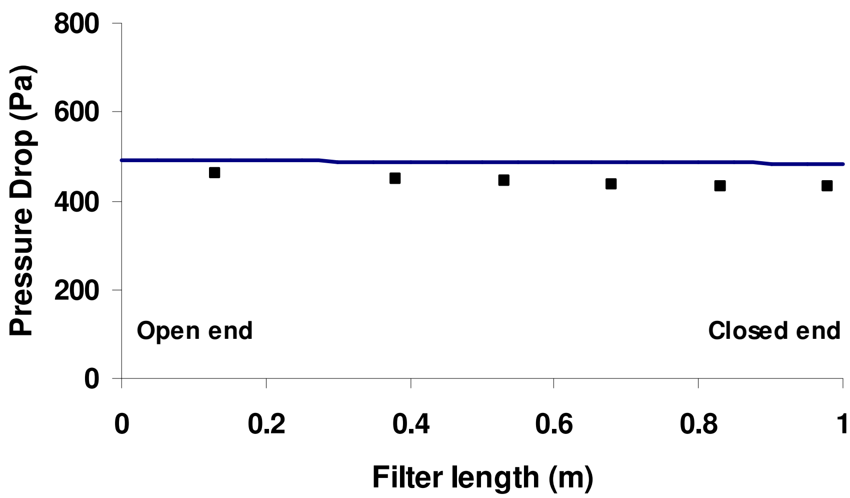


Fig. 7: Prediction of pressure drop along the filter length at face velocity 6 cm/s. Data points is adopted from Chuah (2000).

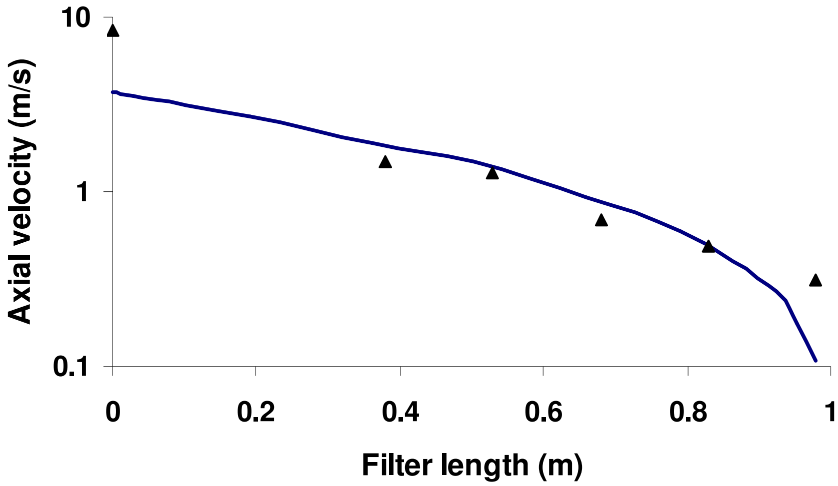


Fig. 8: Prediction of axial velocity along the filter length at face velocity 6 cm/s. Data points is adopted from Chuah (2000).

## 4. Conclusion

The effect of the mean face velocity on the pressure drop along the candle filter has been successfully reproduced numerically via CFD simulation. The CFD code, FLUENT, with the porous media model, predicts very well the pressure drop in candle ceramic filter and may be useful for ceramic filter design. Only a small discrepancy (~ 5%) was observed between the CFD numerical calculations and the experimentally measured pressure drop. Nevertheless, this small discrepancy is thought to be within the magnitude of the experimental error. The evidence of higher velocity magnitude and pressure drop at the open end of the filter candle as it observed experimentally has been also successfully reproduced numerically. Specifically, results obtained from the computer modeling exercise have demonstrated that CFD is a great method for modeling the pressure drop and hydrodynamics of candle filter thus represent a cost effective route for design modification and optimization.

## Acknowledgements

We acknowledge the funding from the research grant IRPA 09-02-04-0702-EA001 ‘Process Simulation and Modeling of Rigid Ceramic Filter for high Temperature Gas Cleaning Industrial Application’.

## References

Ahmadi G, Smith DH, (2002), Analysis of steady-state filtration and backpulse process in a hot-gas filter vessel, *Aerosol Science and Technology* **36**: 665-677.

Al-Hajeri MH, Aroussi A, Simmons K, Pickering SJ, (2005), A parametric study of filtration through a ceramic candle filter, *Proc. IMechE Part A: Journal of Power and Energy* **219**: 77-90.

Aroussi A, Simmons K, Pickering SJ, (2001) Particulate deposition on candle filters, *Fuel* **80**: 335-343.

Chuah TG, Burbidge AS, Tan KK, Seville JPK, (1999), Application of CFD Modelling to the Rigid Ceramic Filter Cleaning Process, *World Engineering Congress 99*, Kuala Lumpur, 19-22 July 1999.

Chuah TG, (2000), *Prediction of the Pressure and Velocity Distributions in Rigid Ceramic Filters*, Ph.D. Thesis, University of Birmingham, UK.

Chuah TG, Withers CJ, Seville JPK, (2004), Prediction and measurements of the pressure and velocity distributions in cylindrical and tapered rigid ceramic filters, *Separation and Purification Technology* **40**: 47-60.

Gamwo IK, Halow JS, Ahmadi G, (2002), Nonisothermal simulation of flows in the hot-gas filter vessel at Wilsonville, *Particulate Science and Technology* **20**: 45-58.

He C, Ahmadi G, (1999), Particle deposition in a nearly developed turbulent duct flow with electrophoresis. *Journal Aerosol Science* **30**: 793–758.

Ito S, Tanaka T, Kawamura S, (1998), Changes in pressure loss and face velocity of ceramic candle filters caused by reverse cleaning in hot coal gas filtration, *Powder Technology* **100**: 32-40.

Kanaoka C, Amornkitbamrung M, (2001), Effect of filter permeability on the release of captured dust from a rigid Ceramic filter surface, *PowderTechnology* **118**: 113–120

Li A., Ahmadi G, Bayer RG, Gaynes MA, (1994), Aerosol particle deposition in an obstructed turbulent duct flow. *Journal Aerosol Science* **25**: 91–112.

Seville JPK, Clift R, Withers CJ, Keidel W. (1989), Rigid Ceramic Media for Filtering Hot Gases. *Filtration & Separation* **26**: 265-271

Seville JPK, (1997), Rigid Ceramic Filters, *In*: Gas Cleaning in Demanding Applications. J. P. K. Seville (editor), Blackie Academic and Professional, Glasgow, 96-129.

Seville JPK, Chuah TG, Sibanda V, Knight P, 2003, Gas cleaning at high temperatures using rigid ceramic filters, *Advanced Powder Technology* **14**: 657-672.

Tanthapanichakoon W, Charinpanitkul T, Jintaworn W, Laksameearunotai J, Amornkitbamrung M, Fukui T, Yoshikawa M, Naito M, (2008), CFD investigation of high-temperature gas filtration using twin ceramic candles, *Powder Technology* **180**: 245-252.

[1]Faculty of Chemical and Natural Resources Engineering, Universiti Malaysia Pahang, UMP, Bandar MEC, 25200 Kuantan, Pahang D.M., Malaysia.

[2]Department of Chemical and Environmental Engineering, Faculty of Engineering,

Universiti Putra Malaysia 43400 UPM Serdang, Selangor D. E., Malaysia.

E-mail: jolius@ump.edu.my