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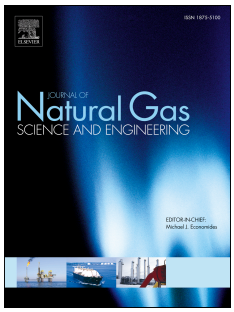

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Large-Scale Study of the Effect of Wellbore Geometry on Integrated Reservoir-Wellbore Flow

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Abstract:

Extraction of coal seam gas (CSG) prior to mining is crucial for reducing the potential risks of gas outburst and explosions during underground coal mining as well as gas production purposes. Many numerical and experimental studies have been carried out to identify the factors affecting the gas productivity. These factors include coal properties, gas content and wellbore geometries. Two different flow conditions determine the gas production efficiency: The gas flow inside the wellbore injected from wall, and the flow through porous coal medium. The full understanding of simultaneous flow of fluids through reservoir and wellbore is critical for analysing the reservoir behaviour. However, previous studies examined the flow of these fluids separately. In this research, a large scale three-dimensional model for simulation of integrated reservoir-wellbore flow is developed to study the effect of wellbore geometry on flow characteristics and wellbore productivity. Four different wellbore diameters of 0.075, 0.10, 0.125 and 0.15 *m* as well as three different lengths of 50, 100, and 150 *m* were chosen to accomplish the parametric study of wellbore geometry. It is assumed that the wellbores were in a steady-state condition for two different single phase scenarios of water and methane gas flow. The simulation results were validated against the pressure drop models for internal single phase gas and water flow reported in the literature. The obtained results revealed that increasing the wellbore diameter led to reduction of fluid pressure in the coal seam. Regarding the effect of wellbore length, it was observed that at a specific distance from wellbore outlet, the pressure distribution is independent of the wellbore length and upstream effects. It is also shown that wellbore production could be enhanced by increasing the diameter and the length of wellbore for both gas and liquid flow. The developed integrated framework can be used further for study of any enhanced gas recovery method by changing the boundary conditions based on the physical model.

Keywords: Reservoir; Wellbore; Coal Seam Gas; Productivity Index; CFD

Nomenclature

D	wellbore diameter, *m*
L	wellbore length, *m*
g	gravitational acceleration, m/s^2
h	reservoir thickness, *m*
J_D	dimensionless productivity index
k	reservoir permeability, m^2
q	volumetric production rate, m^3/s
P	pressure, *Pa*
S_i	momentum sink term, kg/m^2s^2
S_m	mass source term, kg/m^3s
V	velocity, *m/s*
x,y,z	cartesian coordinates, *m*

Greek letters

μ	dynamic viscosity, *Pa s*
ρ	density, kg/m^3
τ	shear stress, *Pa*

Subscript

0	reference values
g	gas phase
l	liquid phase
w	wellbore

1. Introduction

Coal seams naturally contain a large amount of gases such as methane (CH_4) and carbon-dioxide (CO_2). In a general estimation, the gas content for different types of coal varies between 0.1 and 25 m^3 per tonne of coal. Coal seam gas (CSG) is mainly composed of methane (CH_4), which is estimated at 80%-95% of overall gas content. There are still many technical challenges associated with gas production from deep coal seams with high gas content and low permeability. In order to overcome these challenges, wellbores are commonly drilled directionally from vertical to horizontal sections with different diameter and lengths. A reliable prediction of CSG flow depends on the appropriate consideration of coal structure and reservoir properties as well as production wellbore geometry. Previous investigations of CSG production has been focused mainly on either reservoir simulations or wellbore flow characteristics.

Many studies have been carried out to simulate flow of fluids from different types of reservoirs into wellbores (Jenkins and Aronofsky, 1953; Aronofsky and Jenkins, 1954; Al-Hussainy, et al., 1966; Yao, et al., 2013). Early theoretical models or numerical simulations were developed primarily for oil and gas applications. Jenkins and Aronofsky (1953) presented a numerical method for describing the transient flow of gases in a radial direction through a porous medium for which the initial and terminal pressure and/or flow rates are specified. They developed a simple means for predicting the well pressure at any time in the history of a reservoir. In their next study (Aronofsky and Jenkins, 1954) an effective drainage radius was suggested for which the steady-state gas flow assumption could be used to predict the well pressure in the process of gas reservoir depletion. In a rigorous model, Al-Hussainy et al. (1966) considered the effect of variations of pressure dependent viscosity and gas law deviation factor on the flow of real gases through porous media. They used pseudo-pressure as change of variable to reduce the equations to a form similar to diffusivity equations. Yi et

al. (2009) simulated gas flow through a reservoir using a two-dimensional solid-gas coupled software package (RPFA). They studied the effect of permeability, wellbore spacing and diameter and gas content on reservoir pressure and drainage radius. Packman et al. (2011) used SimedWin to simulate CSG flow in an attempt to demonstrate the ability of enhanced gas recovery. Based on their reservoir model calibrated by history matching, they concluded that with regard to increased gas flow rate and decreased drainage time, enhanced gas recovery through injection of nitrogen is achievable. Most of these researches have focused only on reservoir aspects of simulation and their assumptions, such as defined boundary conditions at wellbore and one- or two-dimensional, require further improvements in terms of flow dimensions. The errors associated with the simplifying assumptions limit the range of application of these reservoir simulators. Moreover, the wellbore flow is defined as a boundary condition and is not included in the mathematical modelling and governing equations of the reservoir simulators. These assumptions neglected the interactions between the reservoir and wellbore interfaces.

On the effect of wellbore wall influx/outflux, a number of studies have been carried out to understand the flow filed behaviour and pressure drop along wellbores (Asheim, et al., 1992; Yuan, 1997; Su and Gudmundsson, 1998; Yuan, et al., 1999). Siwon (1987) developed a one-dimensional model for steady state flow of incompressible fluid in a horizontal pipe perforated with circular orifices. Ouyang et al. (1998) continued this study by developing a pressure drop model for pipes with perforated wall that can easily be used in reservoir simulators and analytical models. This model considers different types of pressure drops including frictional, accelerational, gravitational and pressure drop caused by inflow. They concluded that for laminar flow, the wall friction increases due to inflow whereas for turbulent flow, the wall friction decreases as a result of inflow. Based on this approach, more attempts have been made to develop the most accurate pressure drop models for wellbore

flow. Yalniz and Ozkan (2001) investigated the effect of inflow from horizontal wall on flow characteristics and pressured drop experimentally and theoretically. They developed a generalized friction factor correlation that was a function of Reynolds number, the ratios of influx to wellbore flow rate and perforations to wellbore diameter. Wang et al. (2011) measured pressure drop due to inflow in a horizontal perforated pipe loop by using water as working fluid. Their experimental results showed that pressure drop grew as a result of increased injection flow rate. They developed a model suggesting total pressure drop consisting of two parts including perforated pipe wall friction loss and an additional pressure drop term. In a recent study, Zhang et al. (2014) presented a comprehensive model for prediction of pressure drop based on previous studies and some new experiments. Their results show that this model presents more accurate results for their experiments when compared with previous models.

In addition to theoretical models, some researchers have simulated wellbore flow using numerical techniques to avoid the simplifying assumption (Folefac et al., 1991; Seines et al., 1993; Siu, et al., 1995; Su and Lee, 1995; Yuan, et al., 1998; Ouyang and Huang, 2005). Guo et al. (2006) developed a numerical model to study the deliverability of multilateral wells. Their model was capable of coupling the inflow performance of the individual laterals with hydraulics in curved and vertical well sections. Zeboudj and Bahi (2010) simulated wellbore flow with pipe injection using Computational Fluid Dynamics (CFD) simulation as a replacement for further experiments. They discussed the experimental measurement shortcoming in the assumption of a constant momentum-correction factor, which was not true in the case of wall inflow. CFD simulation, however, allowed the exact calculation of this parameter by considering all variations of velocity in radial direction by eliminating the need for making flawed assumptions. In another study, Ouyang et al. (2009) studied single-point wall entry for oil and gas wellbores. The significant effect of wellbore hydraulics on

production predictions, performance evaluations and completion design for horizontal and multilateral wellbores needed to be well understood. In this respect, they used CFD modelling using ANSYS to investigate flow profiles and pressure distribution along the wellbore thoroughly. Their simulation results showed that moving the entry point closer to the outlet section reduced the significant impact of inflow on the total pressure drop along the wellbore.

Depending on wellbore geometry, the flow characteristics through the coal seam and wellbore may vary significantly. Some theoretical models and reservoir simulators have been presented accordingly. However, these models need further improvements with regard to the simplification of boundary condition assumptions on the reservoir-wellbore interface. Efficient production of coal seams gas requires a better understanding of reservoir and wellbore conditions and their interactions. In this study, a large-scale three-dimensional model is developed using CFD simulations to study the integrated reservoir-wellbore flow during CSG production. The specific influence of wellbore diameter and length on the coal seam flow behaviour, pressure drop and production performance is investigated. A schematic of reservoir-wellbore model with assumed boundary conditions is presented in Fig. 1.

2. Mathematical modelling

2.1. Model assumptions

CSG is trapped inside the coal seam by water and ground pressure. The methane gas is maintained inside the coal matrix sealed with water existing in coal fractures (i.e. cleats). As the reservoir pressure at wellbore reduces, the water begins to flow out of cleats letting the gas be desorbed from the coal matrix. Based on the described production process, the following assumptions have been taken into consideration:

- Water is considered as the working fluid for the single phase liquid flow;
- Methane (a compressible ideal gas) is considered as the working fluid for the single phase gas flow;
- The simulations are conducted in the single phase production phase and in the steady state condition;
- Two cell zone conditions for porous coal seam and internal wellbore flow are considered;
- Coal is considered as a homogenous porous media holding gas in the coal matrix;
- Fluid flow through the fracture network of coal obeys Darcy's law;
- Flow through the wellbore is considered turbulent; and
- The flow variables are transferred between wellbore and porous zone by defining an interface at the contact region of the two zones.

One of the most determining parameters, affecting gas production from coal seams, is the coal (reservoir) permeability. Coal permeability varies from near 0.1 to 100 *md* for deep and shallow reservoirs, respectively (Darling, 2011). In this study, the horizontal and vertical permeability of 10 *md* and 1 *md*, respectively, are considered for the coal seam zone. In order to generalize the computed results, the dimensionless parameters, given in Table 1, are defined. The reference values of D_0=0.1 *m*, L_0=100 *m*, P_0=1 *atm*, $\rho_{0,l}$=998.2 kg/m^3, $\rho_{0,g}$=0.67 kg/m^3 are assumed for wellbore diameter, length, pressure, liquid density and gas density, respectively.

2.2. Governing equations

Based on the mentioned assumptions two different sets of equations are required to simulate flow through the wellbore and coal seam. Flow in the wellbore section is considered as

internal turbulent pipe flow with distributed mass transfer through the wall, and flow through the coal seam is treated as a porous media flow.

2.2.1. Wellbore flow equations

Considering varying mass transfer across reservoir-wellbore intersection, the conservation equations of mass momentum and energy can be written as follows:

$$\frac{\partial}{\partial x_i}\left(\rho u_i\right)=0 \tag{1}$$

$$\frac{\partial}{\partial x_j}\left(\rho u_i u_j\right)=-\frac{\partial P}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}-\frac{2}{3}\delta_{ij}\frac{\partial u_l}{\partial x_l}\right)\right]+\frac{\partial \tau_{ij}}{\partial x_j}+\rho\vec{g} \tag{2}$$

where τ_{ij} is the Reynold stress tensor that represents the effect of turbulent fluctuations on fluid flow and is defined by:

$$\tau_{ij}=-\rho\overline{u_i' u_j'} \tag{3}$$

This term is computed using standard $k-\varepsilon$ turbulence models to close the mass and momentum equations. This turbulent model has been widely used and verified for simulation of wellbore flow with wall injection by a number of previous studies (Su, 1996; Yuan, 1997; Ouyang et al., 2009). The details of turbulence models used in the current study with all the constant values can be found in theory guide of the software package (FLUENT, 2011).

2.2.2. Reservoir flow equations

The volume blockage, which is physically present, is not represented in the model. Therefore, a superficial velocity inside the porous medium based on the volumetric flow rate is used. This is to ensure the continuity of velocity vectors across the porous medium interface. The porous medium is modelled by the addition of a momentum sink term to the standard fluid flow equations. To do this, Darcy's flow is considered through the coal fracture network. Under the suggested assumptions for coal seam zone, the conservation equations are written below:

$$\frac{\partial}{\partial x_i}(\rho u_i) = S_m \tag{4}$$

$$\frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_l}{\partial x_l}\right)\right] + \frac{\partial \tau_{ij}}{\partial x_j} + \rho\vec{g} + \vec{S}_i \tag{5}$$

where S_m is the mass source term accounting for the production of gas from coal seam. In order to add mass source term in reservoir zone, internal functions and macros supplied by ANSYS Fluent are compiled in the C programming language and then hooked to the solver. The macro used in this study, specifies the custom mass source term S_m in Eq. (4) at each cell across the reservoir with units of kg/m^3s. The last term in Eq. (5) is defined using Darcy's Law:

$$\vec{S}_i = -\frac{\mu}{k}\vec{v}_i \tag{6}$$

The above momentum sink term contributes to the pressure gradient in the porous cell, creating a pressure drop that is proportional to the fluid velocity in the cell.

2.3. Implementation of computational model

A section of horizontal wellbore is chosen as the base physical model. A 100×5 *m* coal panel with seam thickness of 2.5 *m* and a wellbore diameter of 0.1 *m* is considered as the baseline

condition. Outlet atmospheric pressure boundary condition is applied at the wellbore end. Four different wellbore diameters of 0.075, 0.1, 0.125 And 0.15 *m* as well as three different lengths of 50, 100, and 150 *m* are chosen to accomplish the parametric study of wellbore geometry. The Semi-implicit Method Pressure-linked Equations (SIMPLE) algorithm is used for the pressure–velocity coupling. The second-order upwind discretization scheme is utilized for the momentum, turbulent kinetic energy, and turbulent dissipation rate. The computations are carried out using parallel processing on a high performance computing workstation with 32 nodes. Each node is configured as follows: 2×10 cores @2.60GHz, 128GB RAM.

3. Results and discussion

3.1. Grid convergence and model validation

The computational meshes with high resolution of approximately 1.5 million hexahedral cells were generated with ANSYS Meshing. The average orthogonal quality of 93.2% with standard deviation of 4.8% was achieved for the generated grid. Due to higher pressure gradient at the reservoir-wellbore interface, finer meshes were created near the interface to capture sudden flow variations as presented in Fig. 2. In order to study the grid-independency of simulations, pressure drop along wellbores with different diameters were plotted for three meshes with coarse, medium and fine resolutions as shown in Fig. 3. It is seen that using a higher mesh resolution does not influence the simulation results confirming that a grid-independent solution is achieved.

The simulations are conducted for both methane flow and water flow as the working fluids during the fluid production from underground coal seams. The computed results for methane flow along the wellbore are compared with Atkinson's equation (Le Roux, 1990) to determine the pressure drop using the following equation:

$$\Delta P = \frac{CP_{er}L}{A^3}\frac{\rho}{\rho_{air}}Q^2 \tag{7}$$

where ΔP is the pressure drop (Pa), C is Atkinson friction factor (kg/m^3), P_{er} is wellbore perimeter (m), A is cross-sectional area (m^2), ρ is gas density (kg/m^3), and Q is gas flow rate (m^3/s). The computed pressure drops for four different diameters (coloured with diameters) as well as three different lengths are presented in Fig. 4. The simulation results show good agreement with Atkinson's equation. For the water flow, the simulation results are compared with the following pressure drop model along the pipes (Aziz and Govier, 1972):

$$\Delta P = 2f\frac{\rho V^2 L}{D} \tag{8}$$

$$f = \begin{cases} \dfrac{16}{\mathrm{Re}} & for \quad \mathrm{Re} \le 2200 \\ 0.077716\left\{\log\left[\dfrac{6.9}{\mathrm{Re}} + \left(\dfrac{\varepsilon}{3.7D}\right)^{1.11}\right]\right\}^{-2} & for \quad \mathrm{Re} > 2200 \end{cases} \tag{9}$$

where Re is the Reynold number, ε is the absolute pipe roughness. Same geometries as described for methane flow are now used for water flow (Figure 5). It can be seen that the results are in good agreement with the pressure drop model along pipes.

In order to evaluate the integrated reservoir-wellbore model performance, more simulations were carried out for the case of wellbore-only flow with wall inflow. Velocity inlet with uniform distribution normal to wellbore pipe was defined at wellbore wall to account for methane gas flowing from upstream reservoir. The pressure drop results for the wellbore model is compared with presented integrated reservoir-wellbore model and Atkinson's equation in Table 2. It is seen that the integrated model provides more accurate results compared to wellbore flow model. A close examination of the velocity vectors at the reservoir-wellbore interface for the integrated model shows that the gas is released into the wellbore in the direction of wellbore stream. However, the wellbore-only model

overestimation can be explained by normal direction of wall inflow to main stream and consequently higher pressure drop for accelerating the injected fluid.

The velocity streamlines through coal seam and wellbore are illustrated in Figure 6. As presented in this figure, fluid motion originates from coal seam under the influence of large pressure gradient near the wellbore. It was observed that fluid velocity grows sharply as travelling across the reservoir and towards the wellbore. The presented flow mechanism proves the important influence of efficient wellbore drilling on reservoir production. Development of a three-dimensional integrated model can be considered as a promising tool to improve our understandings about flow field variables and behaviour. These results are essential for advancement of wellbore development plans and study of improved fluid recovery methods where few in-situ data are available due to access limitations and geometrical difficulties. The presented reservoir-model is further evaluated by two parametric studies on the effect of wellbore geometry and length in the following sections.

3.2. Effect of wellbore diameter

Pressure contours at five planes (x^*=0, 0.25, 0.5, 0.75, 1) along and three planes (z^*=−25, 0, 25) across the coal seam for single phase flow of gas and water are illustrated in Fig. 7. It is evident that by increasing the wellbore diameter, the fluid pressure throughout the coal seam decreases. Development of larger wellbores lead to larger production area across the reservoir as well as lower pressure drop and flow resistance along the wellbores. As a result, the model confirms that gas production can be enhanced by development of larger diameter wellbores.

To scrutinise the effect of wellbore diameter on coal seam pressure distribution, the pressure profiles in a vertical direction across the coal seam at x^*=0.5 are plotted (Figure 8). It is observed that the flow pressure increases sharply and reaches approximately a constant value

as moving away from the wellbore to the coal seam in a vertical direction. Comparison of different diameter curves shows that larger diameter wellbores are more effective in reducing the reservoir pressure and higher production.

Velocity profiles for four different wellbore diameters along the wellbore centreline for methane and water flow are presented in Fig. 9. The velocity magnitude varies inversely with wellbore diameter to satisfy the continuity of mass flow rate at the wellbore outlet for similar fluid production from the reservoir. The velocity grows almost linearly moving from the wellbore toe to the heel as the fluid is injected from the wall to the main stream. The velocity profile along a vertical direction at three different sections along wellbore (x^*=0, 0.5, 1) for methane and water flow are presented in Fig. 10. Comparison of velocity profiles at reservoir-wellbore interface shows that the integrated model has captured the sudden velocity increase as moving from reservoir to wellbore. It is also evident that moving from coal seam end to outlet section, the velocity magnitude increases considerably due to continuous injection of fluid along the wellbore.

3.3. Effect of wellbore length

Pressure contours for different wellbore lengths at three planes with similar distance of 0, 25, 50 *m* from wellbore outlet and three planes (z^*=−25, 0, 25) across the coal seam for single phase methane flow are presented in Fig. 11. These three planes along the wellbore are chosen to investigate the influence of upstream effects on production behaviour and pressure distribution through coal seams with longer wellbores. Pressure through the coal seam in the far from wellbore regions does not vary significantly along the coal seam in the *x* direction. This behaviour can be explained by the greater value of coal permeability in the horizontal plane compared to the vertical plane. The pressure contours for the three cases show that for a

specific distance from the wellbore outlet, the pressure distribution is almost independent of wellbore length and upstream effects.

This observation is investigated further by studying pressure profiles across the horizontal and vertical directions through coals seams of different lengths (x^*=0.5, 1, 1.5) as presented in Fig. 12. As can be seen, at a similar distance from the wellbore outlet, the upstream wellbore flow does not influence pressure distribution across the reservoir. The pressure increases more sharply when moving away from the wellbore in the *y* direction due to higher permeability in vertical plane compared to horizontal plane. Velocity profiles across the vertical direction at a distance of 25 *m* from the wellbore outlet for three different coal seam lengths (x^*=0.5, 1, 1.5) are presented in Fig. 13. It is evident that the longest coal seam has the highest velocity magnitude across the wellbore which can be explained by the higher injection from upstream reservoir to the wellbore. Similar observations, presented in Figs. 11-13, are observed for the effect of wellbore length on single phase water flow through coal seam and wellbore.

3.4. Effect of wellbore geometry on productivity index

One of the appropriate tools for evaluating the wellbore performance in petroleum engineering is productivity index (PI) which is defined as the ratio of produced liquid flow rate to pressure drawdown. In order to study the effect of wellbore geometry on wellbore performance, dimensionless productivity index (J_D) is calculated as follows:

$$J_D = \frac{\mu}{2\pi kh} \times \frac{q}{\overline{P} - P_w} \tag{10}$$

The effect of wellbore dimeter and length on productivity index for the single phase methane flow and water flow is presented in Fig. 14. Regarding the impact of wellbore diameters, the CFD results show that increasing the diameters leads to higher PI which is consistent with

previous findings. Similar behaviour is observed on the effect of wellbore length considering greater production volume for longer reservoir sections. The presented simulations and case studies verifies the improved capability of the current integrated reservoir-wellbore model as a promising tool for further studies of enhanced fluid recovery.

4. Conclusions

A three-dimensional CFD model for the simulation of integrated reservoir-wellbore flow is developed to study the significant effect of wellbore geometry on flow characteristics of coal seams. Four different wellbore diameters and three lengths are simulated for single phase methane and water flow. The numerical simulation results show that by increasing the wellbore diameters the fluid pressure throughout the coal seam falls, resulting in more efficient production from coal seam. It can also be seen that the velocity magnitude is remarkably larger across wellbore than through reservoir and moving from coal seam end to outlet section, the velocity magnitude increases considerably due to continuous injection of fluid along the wellbore. Pressure distribution through the coal seam in the far from wellbore regions does not vary significantly along the wellbore due to higher permeability of porous media in horizontal plane. In addition, the computational results indicate that for a specific distance from the wellbore outlet, the pressure distribution is almost independent of wellbore length and upstream effects. It is confirmed that with increasing the wellbore diameters and lengths the wellbore productivity index is enhanced. This study proves that the presented CFD model can be used as a promising tool for study of wellbore performance predictions as well as enhanced fluid recovery methods. This model can provide the engineers with in-situ data using an inexpensive and flexible computer model.

References

Al-Hussainy, R., H. Ramey Jr and P. Crawford (1966). "The flow of real gases through porous media." Journal of Petroleum Technology **18**(05): 624-636.

Aronofsky, J. and R. Jenkins (1954). "A simplified analysis of unsteady radial gas flow." Journal of Petroleum Technology **6**(07): 23-28.

Asheim, H., J. Kolnes and P. Oudeman (1992). "A flow resistance correlation for completed wellbore." Journal of Petroleum Science and Engineering **8**(2): 97-104.

Aziz, K. and G. W. Govier (1972). The Flow of Complex Mixtures in Pipes [by] GW Govier and K. Aziz, New York: Van Nostrand Reinhold Company.

Darling, P. (2011). SME Mining Engineering Handbook. Littleton, SME.

Fluent, A. (2011). "Ansys Fluent Theory Guide." ANSYS Inc., USA.

Folefac, A. N., J. S. Archer, R. I. Issa and A. M. Arshad (1991). Effect of Pressure Drop Along Horizontal Wellbores on Well Performance, Society of Petroleum Engineers.

Guo, B., K. Ling and A. Ghalambor (2006). A Rigorous Composite-IPR Model for Multilateral Wells, Society of Petroleum Engineers.

Jenkins, R. and J. Aronofsky (1953). "Unsteady radial flow of gas through porous media." Journal of Applied Mechanics-Transactions of the ASME **20**(2): 210-214.

Le Roux, W. (1990). Le Roux's Notes on Mine Environmental Control, Mine Ventilation Society of South Africa.

Ouyang, L.-B., S. Arbabi and K. Aziz (1998). "General Wellbore Flow Model for Horizontal, Vertical, and Slanted Well Completions."

Ouyang, L.-B. and W. S. B. Huang (2005). A Comprehensive Evaluation of Well-Completion Impacts on the Performance of Horizontal and Multilateral Wells, Society of Petroleum Engineers.

Ouyang, L. C., D. Sun and L. B. Ouyang (2009). "Numerical Investigation of the Impacts of Wall Fluid Entry on Fluid Flow Characteristics and Pressure Drop along a Wellbore." Petroleum Science and Technology **27**(18): 2109-2133.

Packham, R., Y. Cinar and R. Moreby (2011). "Simulation of an enhanced gas recovery field trial for coal mine gas management." International Journal of Coal Geology **85**(3–4): 247-256.

Seines, K., I. Aavatsmark, S. C. Lien and P. Rushworth (1993). "Considering wellbore friction effects in planning horizontal wells." Journal of Petroleum Technology; (United States); Journal Volume: 45:10: Medium: X; Size: Pages: 994-1000.

Siu, A., D. Shin and G. Subramanian (1995). A Complete Hydraulics Model for Horizontal Wells, Society of Petroleum Engineers.

Siwoń, Z. (1987). "Solutions for Lateral Inflow in Perforated Conduits." Journal of Hydraulic Engineering **113**(9): 1117-1132.

Su, Z. (1996). "Pressure drop in perforated pipes for horizontal wells", Norwe-gian University of Science and Technology, Trondheim, Norway.

Su, H. J. and S. H. Lee (1995). "Modeling Transient Wellbore Behavior in Horizontal Wells", Society of Petroleum Engineers.

Su, Z. and J. S. Gudmundsson (1998). "Perforation inflow reduces frictional pressure loss in horizontal wellbores." Journal of Petroleum Science and Engineering **19**(3–4): 223-232.

Wang, Z., J. Xiao, X. Wang and J. Wei (2011). "Experimental study for pressure drop of variable mass flow in horizontal well." J. Exp. Fluid Mech **25**(5): 26-29.

Yalniz, M. U. and E. Ozkan (2001). "A Generalized Friction-Factor Correlation To Compute Pressure Drop in Horizontal Wells."

Yao, S., F. Zeng, H. Liu and G. Zhao (2013). "A semi-analytical model for multi-stage fractured horizontal wells." Journal of Hydrology **507**: 201-212.

Yi, L.-j., Z.-l. Tang and Q.-x. Yu (2009). Computer simulation of gas pressure and drainage radius for dense wellbores gas pre-drainage in outburst coal seam. Computer Science & Education, 2009. ICCSE '09. 4th International Conference on.

Yuan, H. (1997). Investigation of single phase liquid flow behavior in horizontal wells, in, University of Tulsa, 1997.

Yuan, H., C. Sarica and J. P. Brill (1998). Effect of Completion Geometry and Phasing on Single-Phase Liquid Flow Behavior in Horizontal Wells, Society of Petroleum Engineers.

Yuan, H. J., C. Sarica and J. P. Brill (1999). "Effect of Perforation Density on Single-Phase Liquid Flow Behavior in Horizontal Wells."

Zeboudj, F. and L. Bahi (2010). Horizontal Well Performance Flow Simulation CFD-Application, Society of Petroleum Engineers.

Zhang, Q., Z. Wang, X. Wang and J. Yang (2014). "A New Comprehensive Model for Predicting the Pressure Drop of Flow in the Horizontal Wellbore." Journal of Energy Resources Technology **136**(4): 042903-042903.

Figure Captions

Fig. 14 – Productivity index for different wellbore geometries. a) wellbore diameter; b) wellbore lengths

Table caption

Table 1. Dimensionless parameters

Table 2. Comparison of wellbore-only model with integrated reservoir-wellbore model

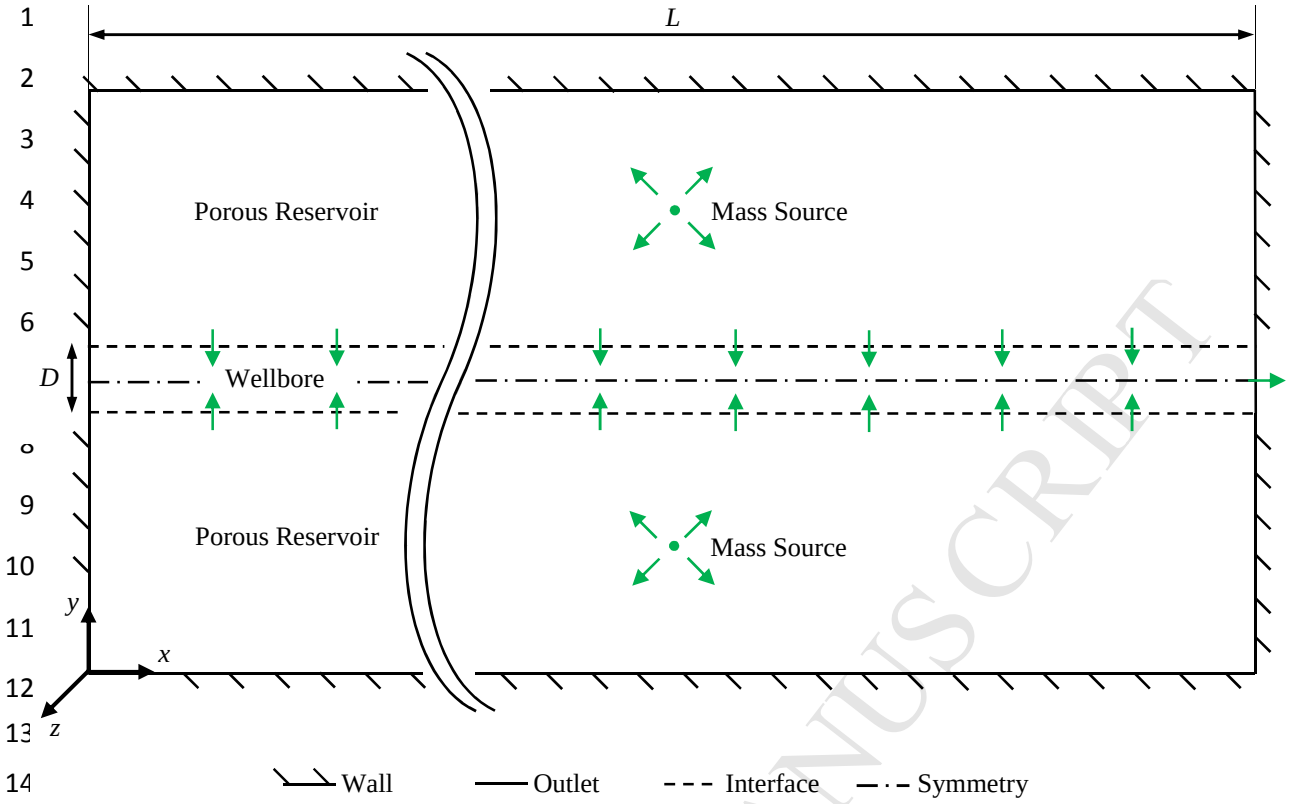

Fig. 1 – A schematic diagram of reservoir-wellbore model

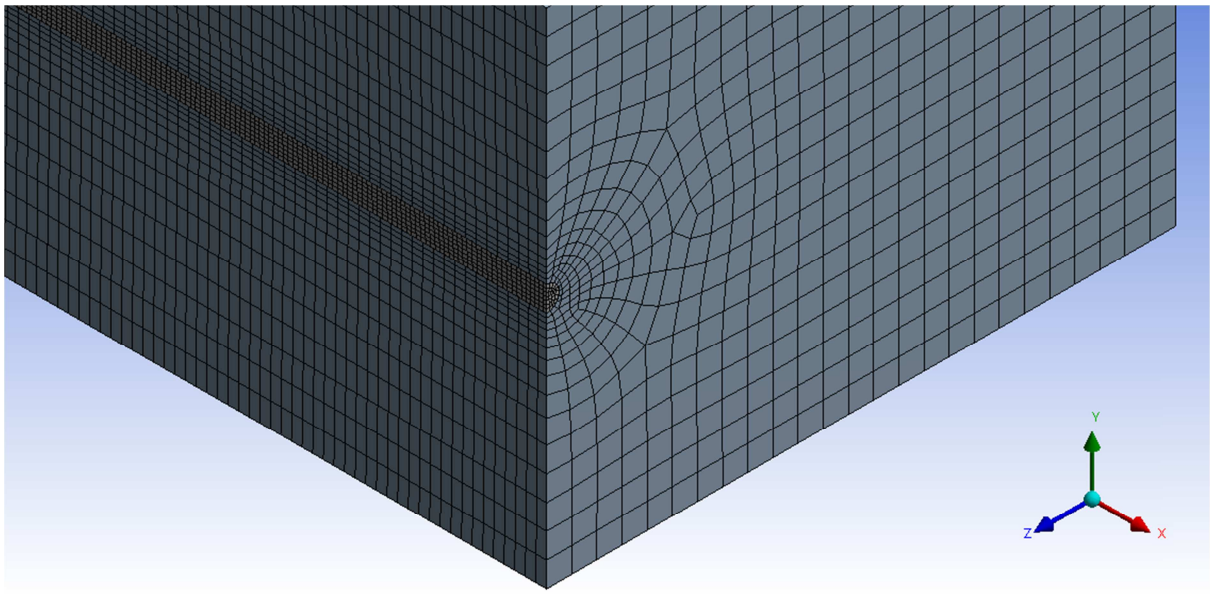

Fig. 2 – Computational mesh of reservoir-wellbore model

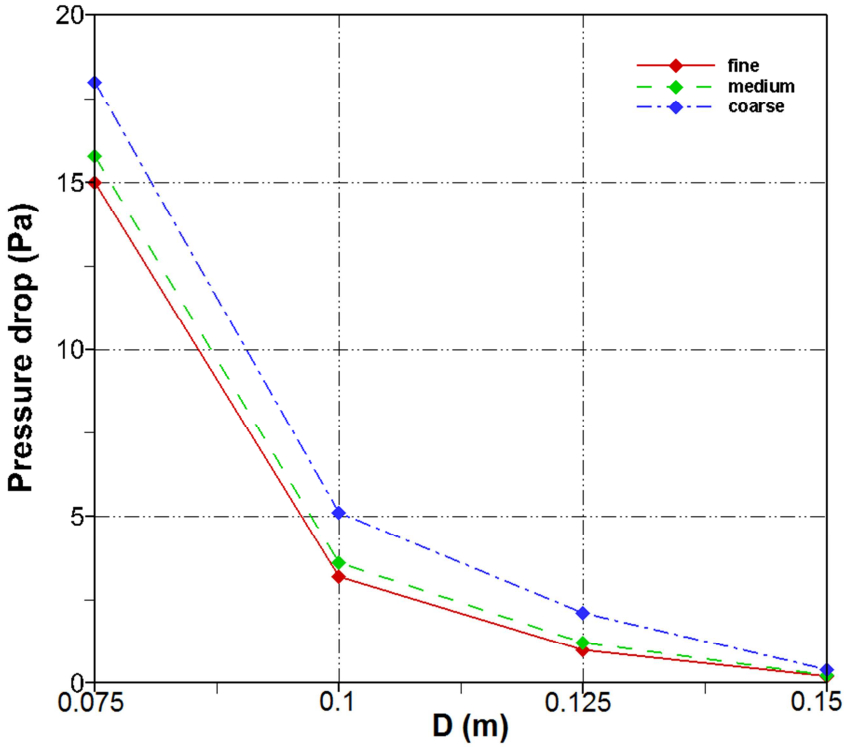

Fig. 3 – Pressure drop vs. wellbore dimeter for methane flow with different mesh resolutions

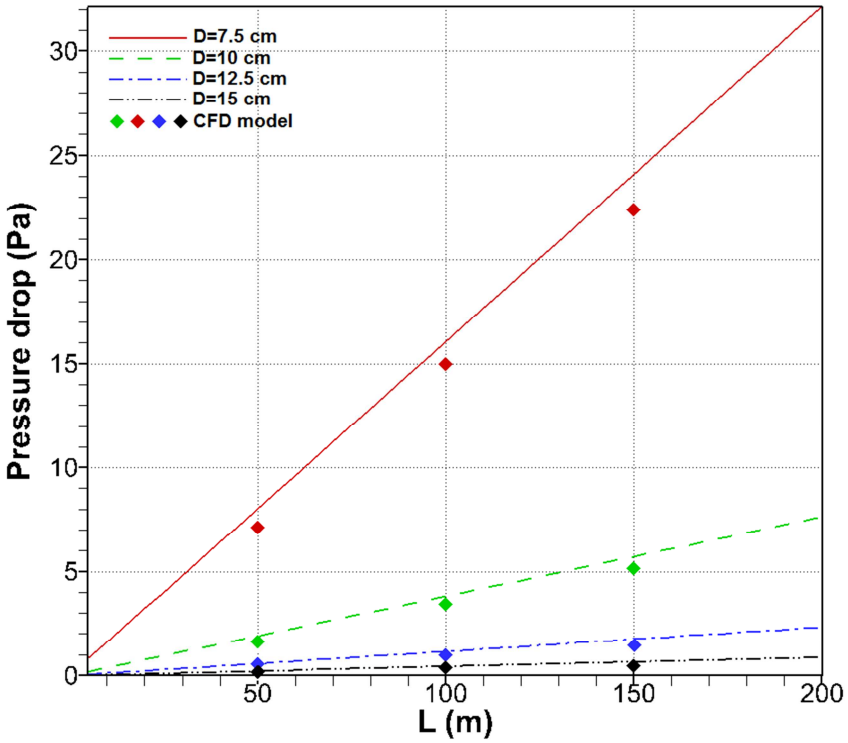

Figure 4 – Comparison of simulated model for methane flow with Atkinson equation (Le Roux, 1990)

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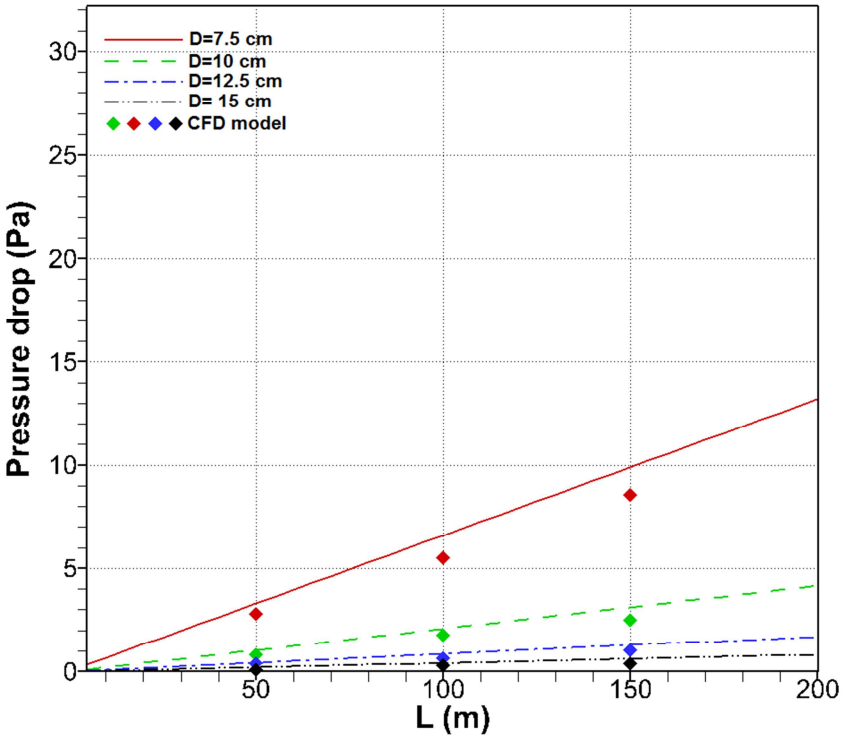

Figure 5 – Comparison of simulated model for water flow with (Aziz and Govier, 1972) correlation

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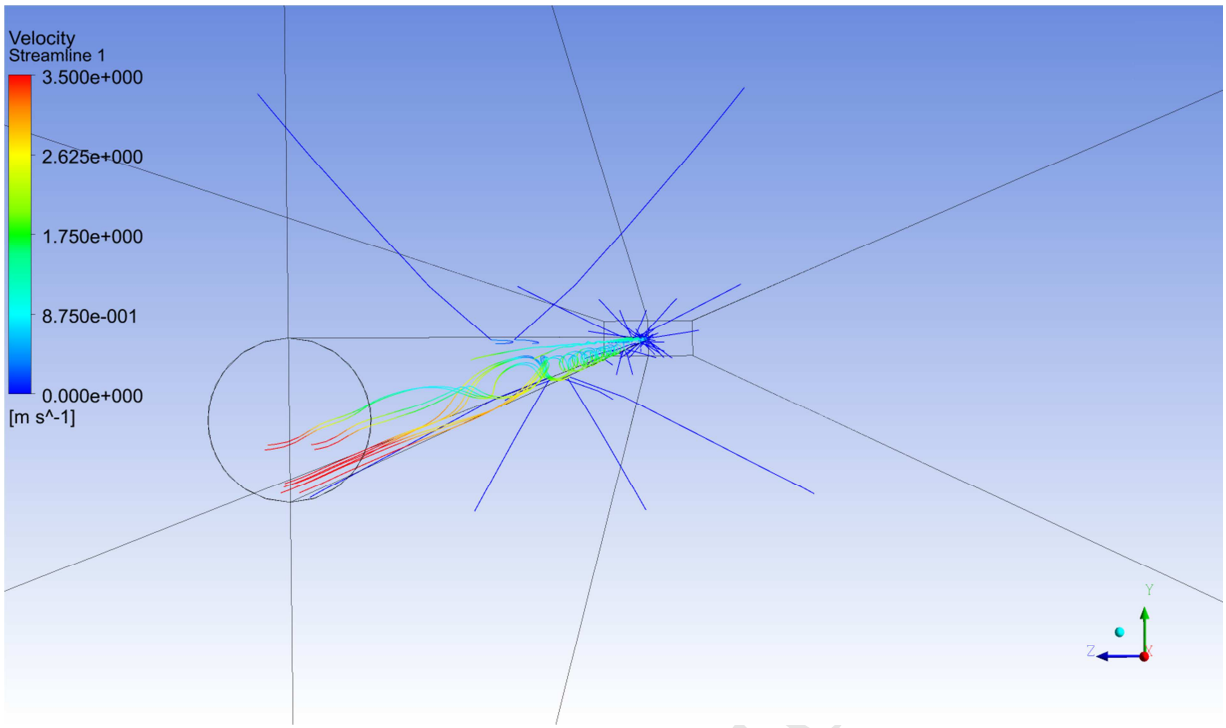

Figure 5 – Velocity streamlines through coal seam reservoir and wellbore

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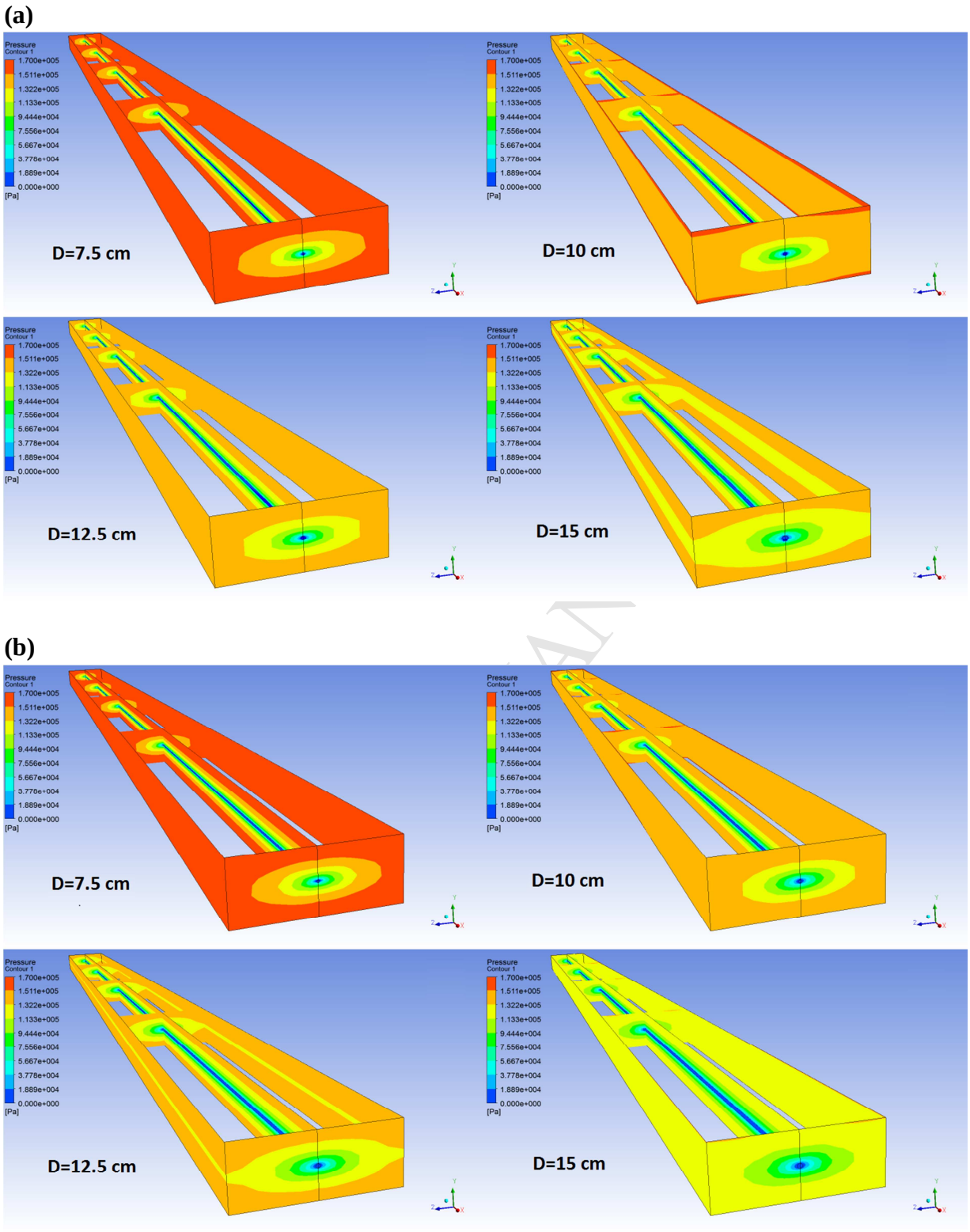
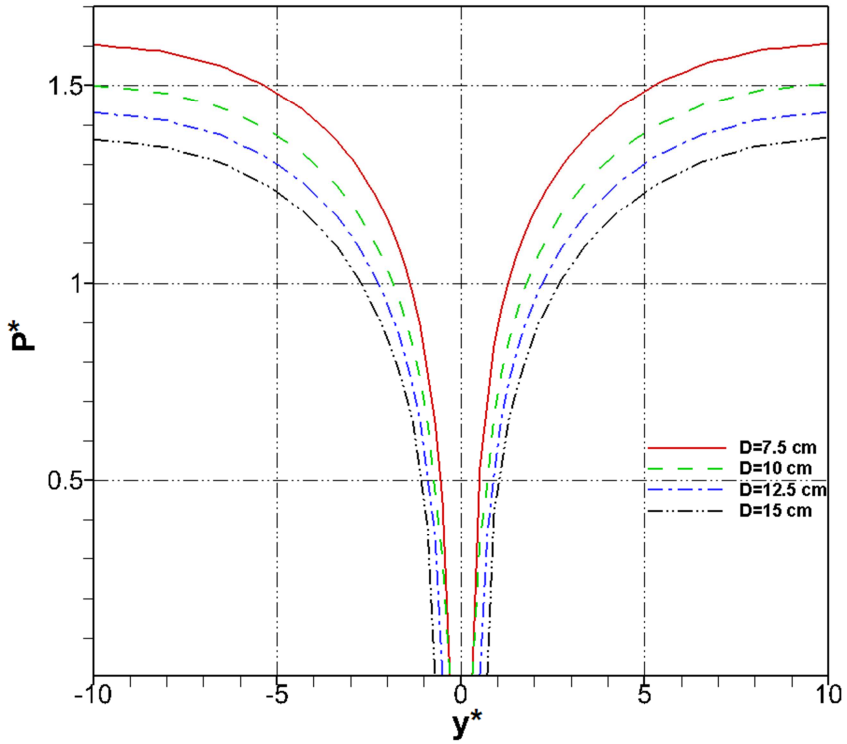


Figure 6 – Pressure contours along coal seam for different wellbore diameters for: a) methane flow, and b) water flow

(a)



(b)

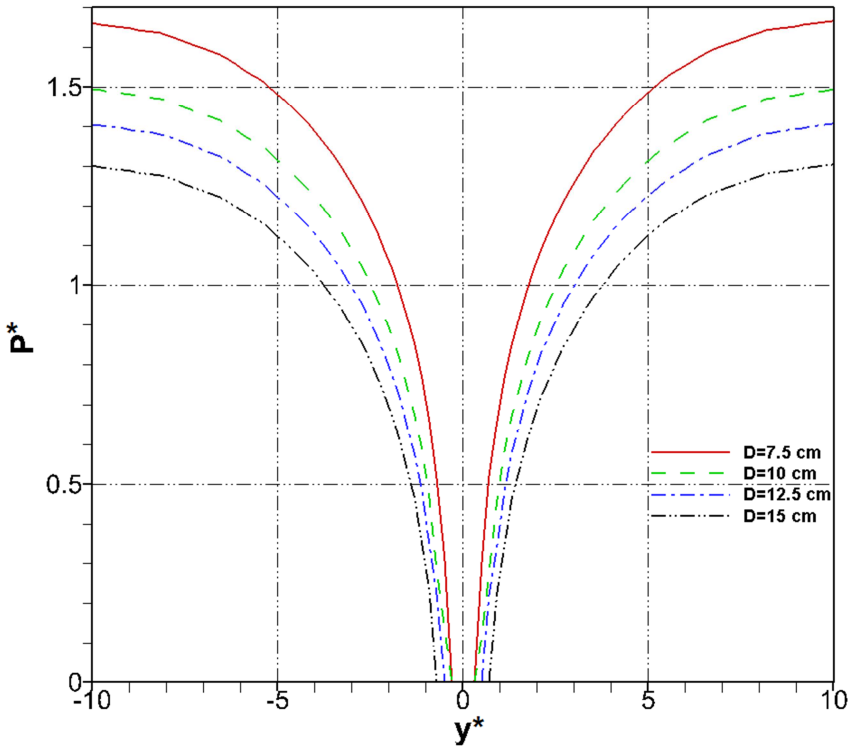


Figure 7 – Pressure distribution in *y* direction across coal seam at x^*=0.5 for: a) methane flow, and b) water flow

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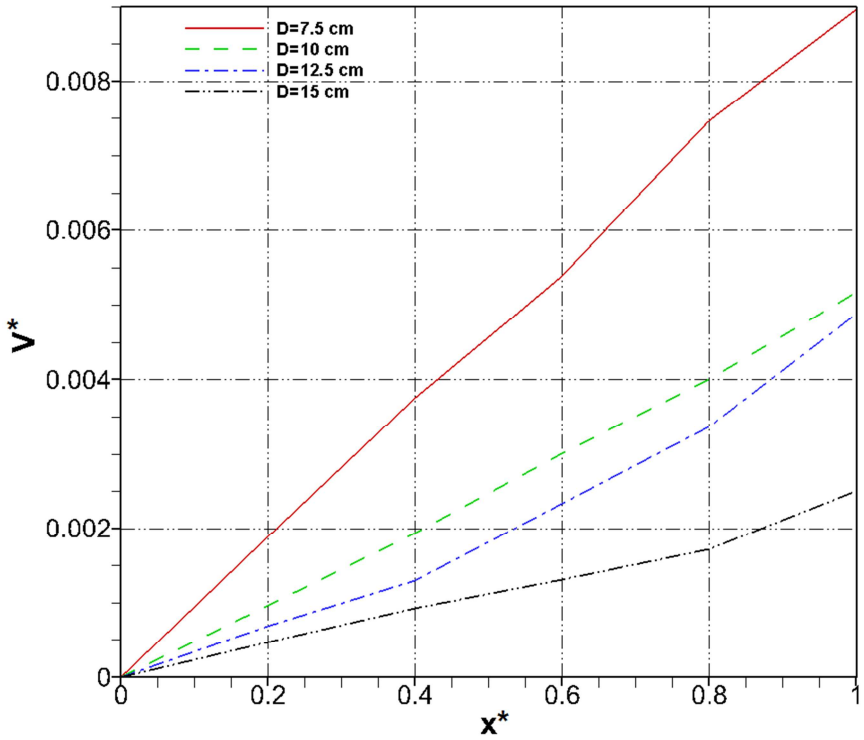
(a)



(b)

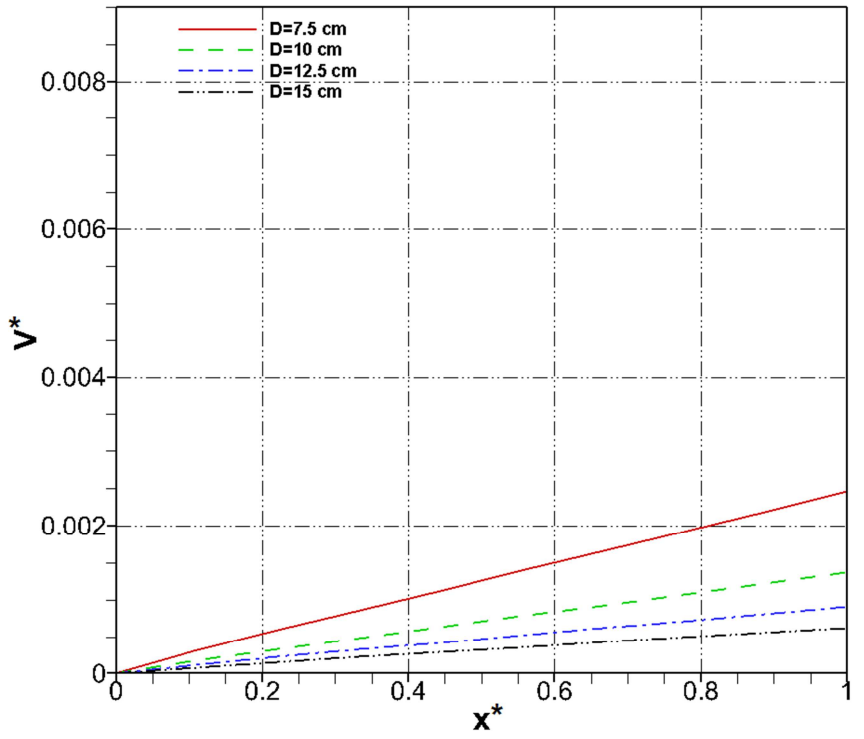


Figure 8 – velocity along wellbore centreline for: a) methane flow, and b) water flow

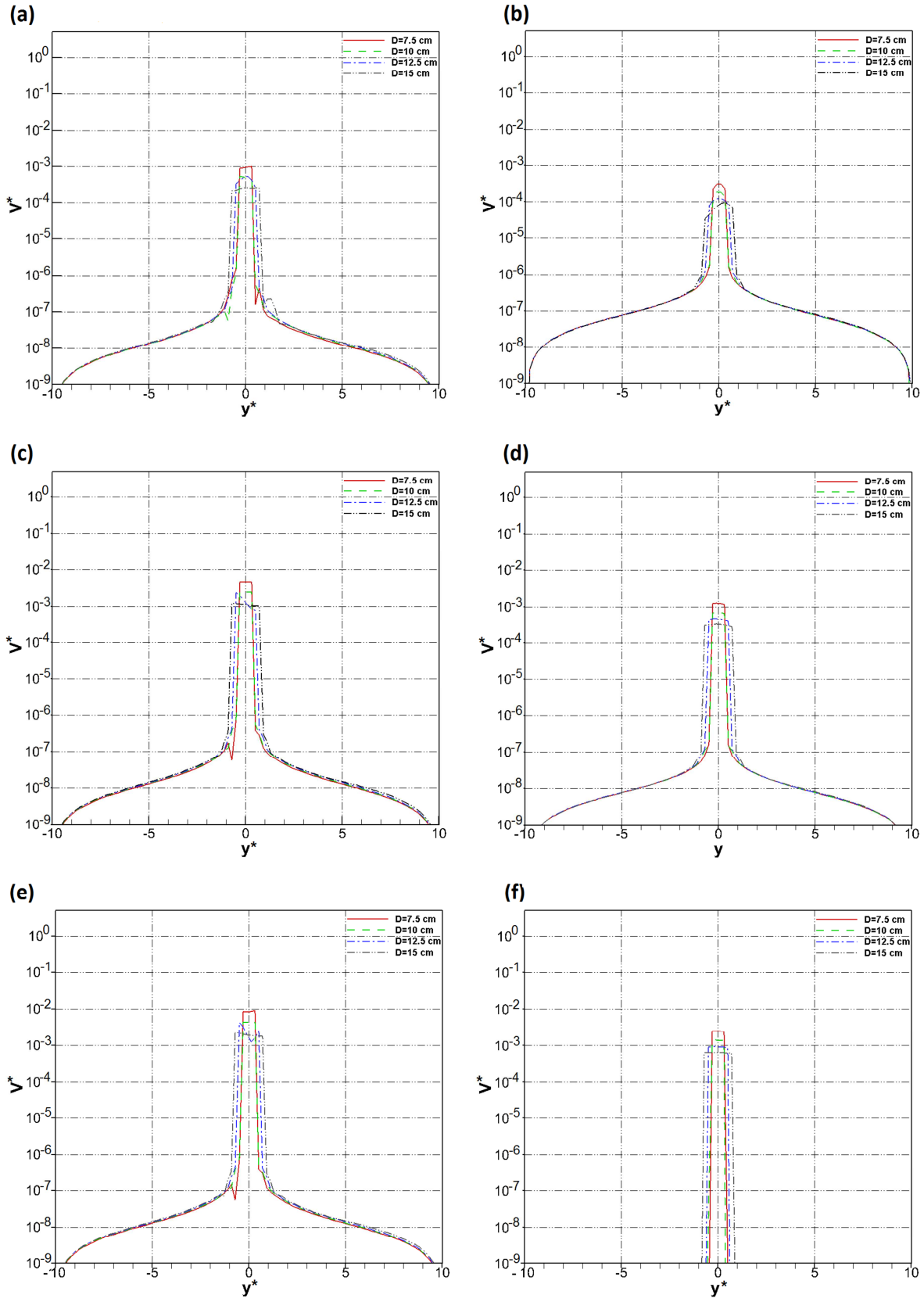


Figure 9 – Velocity profile along Y direction for methane (left) and water (right) flow at: a,c) x^*=0; b,d) x^*=0.5; e,f) x^*=1

1

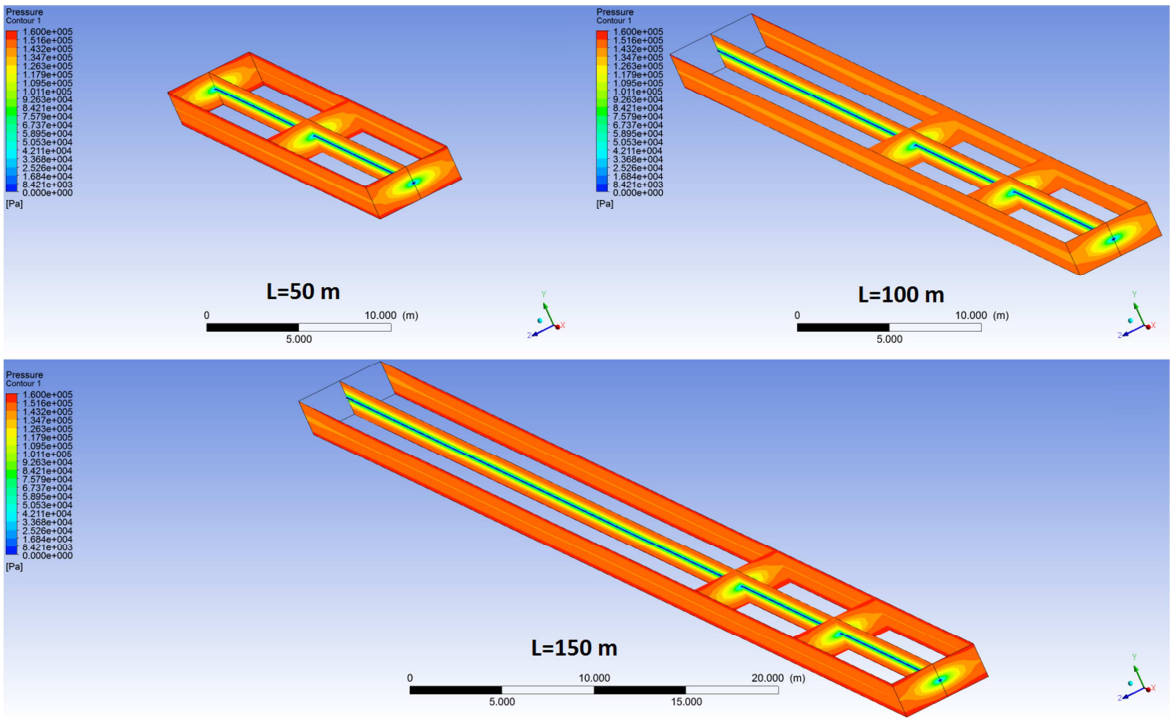


Figure 10 – Pressure contours along coal seam for different wellbore lengths

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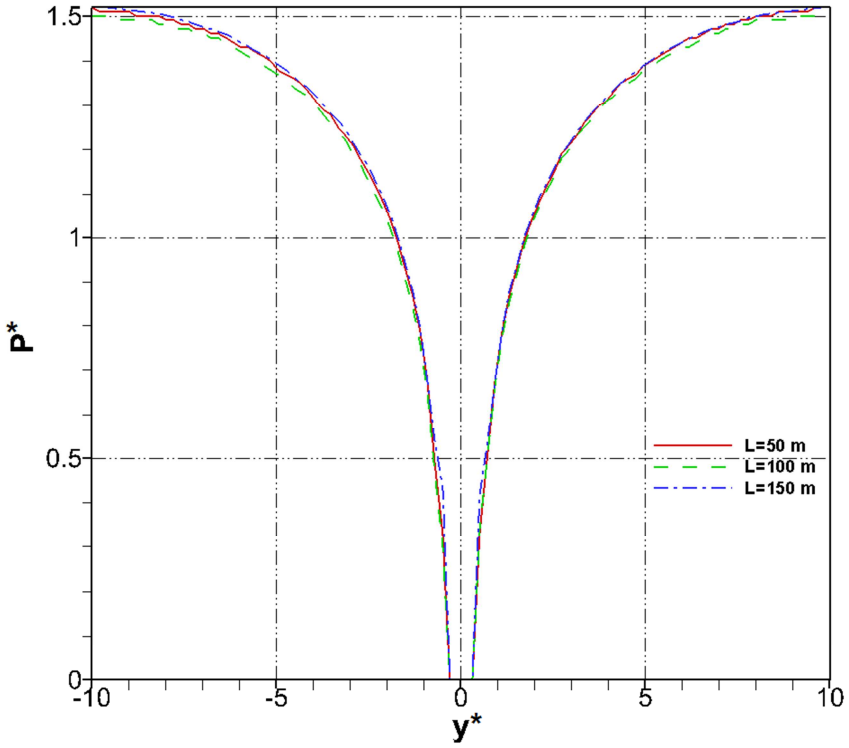
(a)



(b)

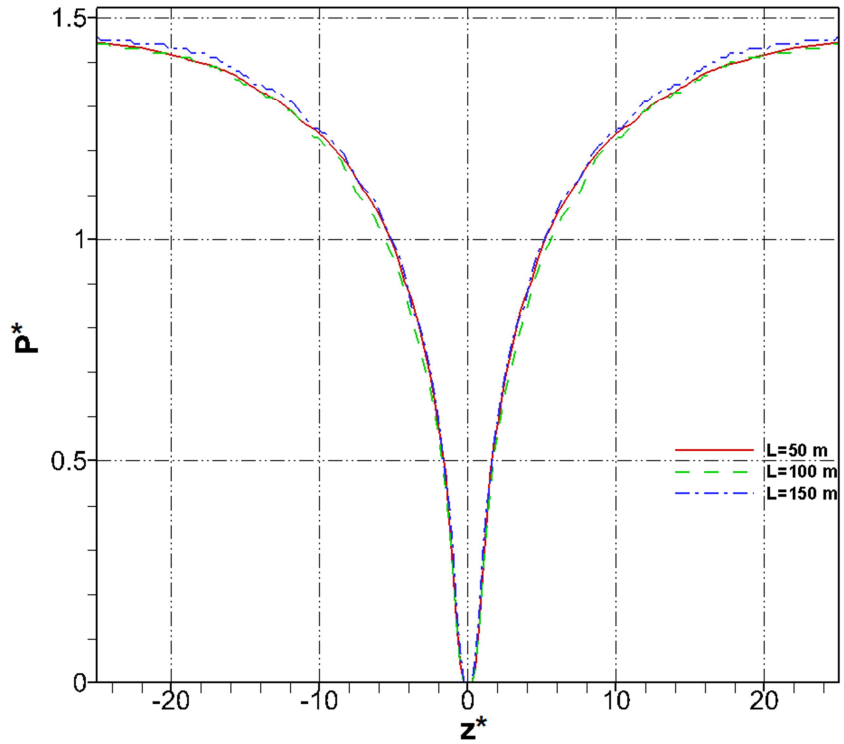


Figure 11– Pressure distribution at distance of 25 m from wellbore outlet in: a) *y* direction, and b) *z* direction

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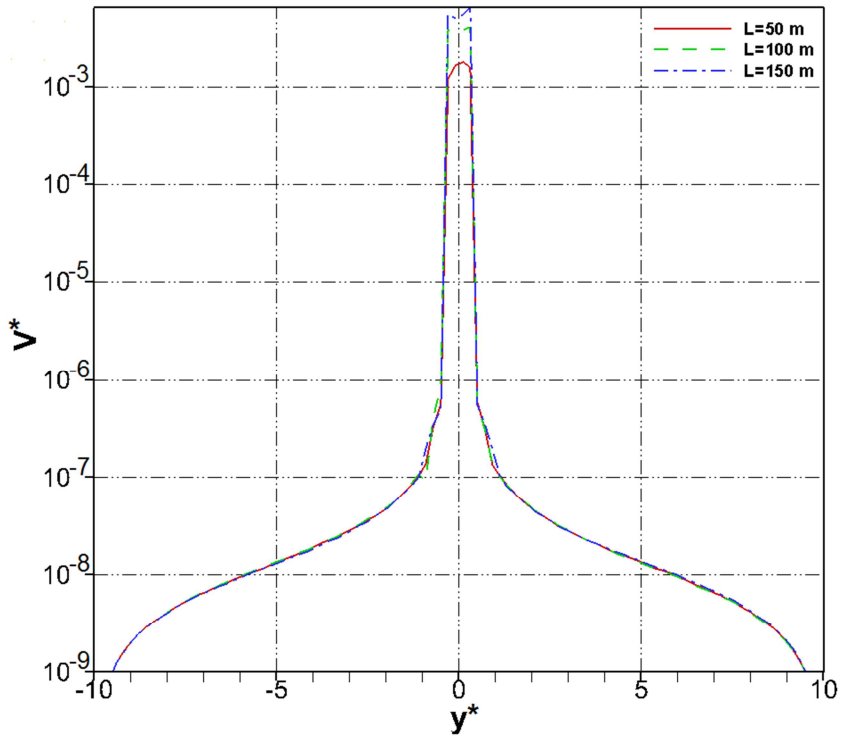

Figure 12 – Velocity profile along *y* direction at the distance of 25 m from wellbore outlet for different wellbore lengths

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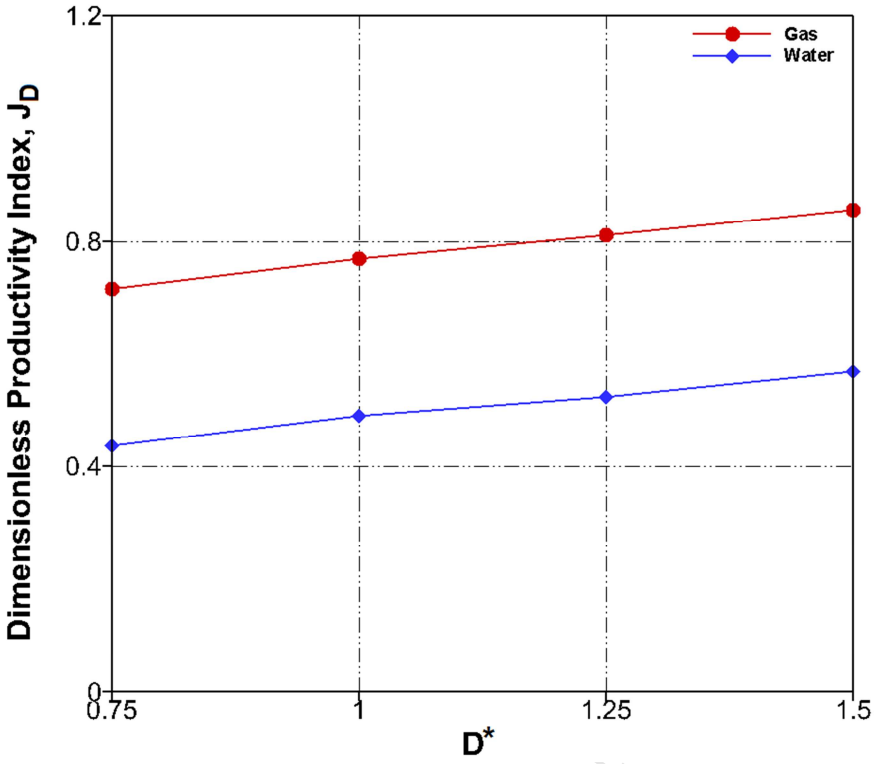
(a)



(b)

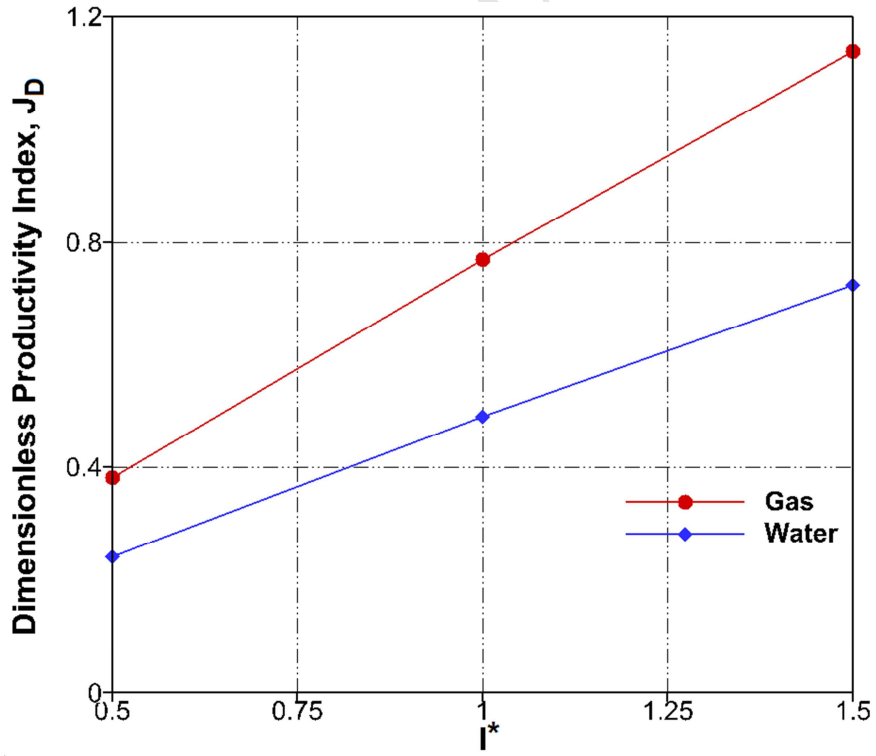


Figure 13 – Productivity index for different wellbore geometries. a) wellbore diameter; b) wellbore length

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Table 1. Dimensionless parameters

Variable type	Dimensionless parameters	
Independent variables	$x^* = \frac{x}{L_0}$	$y^* = \frac{y}{D_0}$
	$z^* = \frac{z}{D_0}$	$l^* = \frac{l}{L_0}$
Dependant variables	$V^* = \frac{V}{\sqrt{P_0 / \rho_0}}$	$p^* = \frac{p}{p_0}$

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Table 2. Comparison of wellbore-only model with integrated reservoir-wellbore model

Wellbore dimensions (m)	Pressure drop (Pa)		Relative error* (%)	
	Reservoir-only	Integrated reservoir-wellbore	Reservoir-only	Integrated reservoir-wellbore
D=0.075, L=100	18.59	15.02	15.7	6.5
D=0.10, L=100	4.77	3.46	25.1	9.2
D=0.125, L=100	1.74	1.07	49.4	8.1
D=0.15, L=100	0.6	0.41	37.9	5.7
D=0.10, L=50	2.45	1.73	28.6	9.2
D=0.10, L=150	6.85	5.28	19.8	7.6

1 * realtive errors are calculated based on Atkinson's equation

Highlights:

- An integrated CFD model of reservoir-wellbore flow was developed.
- Fluid production can be enhanced by increasing the wellbore diameter and length.
- Increasing the wellbore diameter leads to pressure reduction through coal seam.
- At a certain distance from wellbore outlet, pressure is independent of upstream flow.