

COMPRESSIBLE GAS FLOW THROUGH THE DIFFUSIBLE BARRIERS AND THE POROUS MEDIA

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Abstract: *This paper is focused on the numerical simulation of the compressible gas flow through the porous media and through the diffusible barriers. We work with the non-stationary viscous compressible fluid flow, described by the RANS equations. The flow through the porous media is characterized by the loss of momentum. For the simulation of the diffusible barrier we analyze the modification of the Riemann problem with one-side initial condition, complemented with the Darcy's law and added inertial loss. The presented examples were obtained with the own-developed code for the solution of the compressible gas flow.*

Keywords: compressible gas flow, diffusible barriers, the RANS equations, the Riemann problem, boundary conditions

1. Introduction

We work with the compressible fluid motion described by the conservation laws of mass, momentum, and energy. These fundamental conservation laws form a system of partial differential equations (the Euler equations, the Navier-Stokes equations, the Navier Stokes equations with turbulent models). We choose the well-known finite volume method to discretize the analytical problem, represented by the system of the equations in generalized (integral) form. We split the area of the interest into the elements, and we construct a piecewise constant solution in time. The crucial problem of this method lies in the evaluation of the so-called fluxes through the faces of the elements. Here we use the analysis of the Riemann problem to construct these fluxes. The analysis of the Riemann problem with original modifications is used at the boundary (see Kyncl (2011); Kyncl and Pelant (2014, 2016)), and for the simulation of the diffusible barrier, presented also in Kyncl and Pelant (2013), and further developed in Kyncl and Pelant (2017). Here we show own algorithm for the solution of the boundary problem at the diffusible barrier, and we use it in the numerical examples.

2. Equations

The system of conservation laws can be written in the following vector form

$$\frac{\partial \mathbf{w}}{\partial t} + \sum_{s=1}^3 \frac{\partial \mathbf{f}_s(\mathbf{w})}{\partial x_s} = \sum_{s=1}^3 \frac{\partial \mathbf{R}_s(\mathbf{w}, \nabla \mathbf{w})}{\partial x_s} + \mathbf{S}(\mathbf{w}) \quad \text{in } Q_T = \Omega \times (0, T). \quad (1)$$

Here $\mathbf{w} = \mathbf{w}(x, t)$ is the state vector, $x \in \Omega$, t denotes the time, Q_T is the space-time cylinder, \mathbf{f}_s are the inviscid fluxes, \mathbf{R}_s are the viscous fluxes, \mathbf{S} is the source-term vector. Further we use the equation of state of ideal gas, and the turbulent model equations.

3. Porous media simulation

The porous media is simulated using the modification of the system of equations (1). The simple porous media can be simulated via the new source term, written as

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$$\mathbf{S} = \begin{pmatrix} 0 \\ -\frac{\mu}{\alpha} v_1 - C_0 \frac{\rho}{2} |\mathbf{v}| v_1 + \rho g_1 \\ -\frac{\mu}{\alpha} v_2 - C_0 \frac{\rho}{2} |\mathbf{v}| v_2 + \rho g_2 \\ -\frac{\mu}{\alpha} v_3 - C_0 \frac{\rho}{2} |\mathbf{v}| v_3 + \rho g_3 \\ -\frac{\mu}{\alpha} \mathbf{v}^2 - C_0 \frac{\rho}{2} |\mathbf{v}| \mathbf{v}^2 + \rho \mathbf{g} \cdot \mathbf{v} \end{pmatrix} \quad (2)$$

Here α is the permeability coefficient, C_o is the pressure gradient coefficient, ρ is the density, $\mathbf{v} = (v_1, v_2, v_3)$ is the velocity vector, $\mathbf{g} = (g_1, g_2, g_3)$ is the gravitational acceleration vector, μ denotes the dynamic viscosity. The source term (2) was implemented into own-developed software, Figure 1 shows computed example.

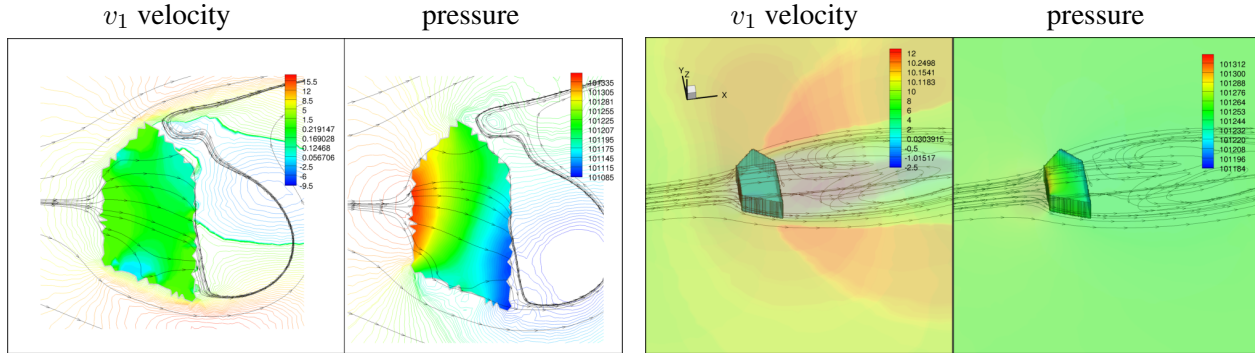


Fig. 1: The compressible gas flow through the polygonal porous area, isolines of v_1 velocity component and the pressure, computational results for the regime $10 \text{ [m s}^{-1}\text{]}$, 2D inviscid simulation, and 3D viscous turbulent simulation in the gravitational field.

4. Boundary condition for the diffusible barrier

Here we present the diffusible barrier condition as a combination of Darcy's law with the additional inertial losses.

$$\frac{\Delta p}{\Delta m} = - \left(\frac{\mu}{\alpha} U + C_o \frac{1}{2} R U^2 \right), \quad (3)$$

where $\Delta p = p_2 - p_1$ is the pressure difference across the barrier, Δm is the thickness of the barrier (example $\Delta m \in (0.01, 0.05)$), μ is the dynamic viscosity, α the permeability coefficient (example $\alpha = 10^{-8}$), C_o is the pressure gradient coefficient (example $C_o = 10^2$), R the density at the barrier, and U is the velocity at the barrier. The equation (3) can be rewritten in the form

$$R U^2 + C U = d(p_1 - p_2), \quad (4)$$

here $C = \frac{2\mu}{\alpha C_o} > 0$, $d = \frac{2}{\Delta m C_o} > 0$, $(p_1 - p_2) \geq 0$. We are interested in the boundary values R, U, P at the barrier. Further we require that the conservation laws (1D Euler equations) are satisfied in the close vicinity of the barrier

$$\frac{\partial}{\partial t} \begin{pmatrix} \rho \\ \rho u \\ E \end{pmatrix} + \frac{\partial}{\partial \tilde{x}_1} \begin{pmatrix} \rho u \\ \rho u^2 + p \\ (E + p) u \end{pmatrix} = 0, \quad t \in (0, \infty), \tilde{x}_1 \in (-\infty, \infty). \quad (5)$$

Here the axis \tilde{x}_1 is perpendicular to the barrier, $\rho(\tilde{x}_1, t)$ denotes the density, $p(\tilde{x}_1, t)$ is the pressure, $u(\tilde{x}_1, t)$ is the velocity (with the direction perpendicular to the barrier), $E(\tilde{x}_1, t)$ denotes the total energy: $E = \rho u^2/2 + p/(\gamma - 1)$. The initial condition is formed by the two states near the barrier. Let us denote these states ρ_1, u_1, p_1 (for $\tilde{x}_1 < 0$) and ρ_2, u_2, p_2 (for $\tilde{x}_1 > 0$). Further we think of the barrier problem as of two boundary problems (for the inlet, and for the outlet) with the two particular solutions (different in general). The analysis of these problems was shown in Kyncl and Pelant (2017), Figures 2, 3 show the resulting algorithm. We suppose the initial velocity $u_1 \geq 0$, and we seek the solution with $U > 0$.

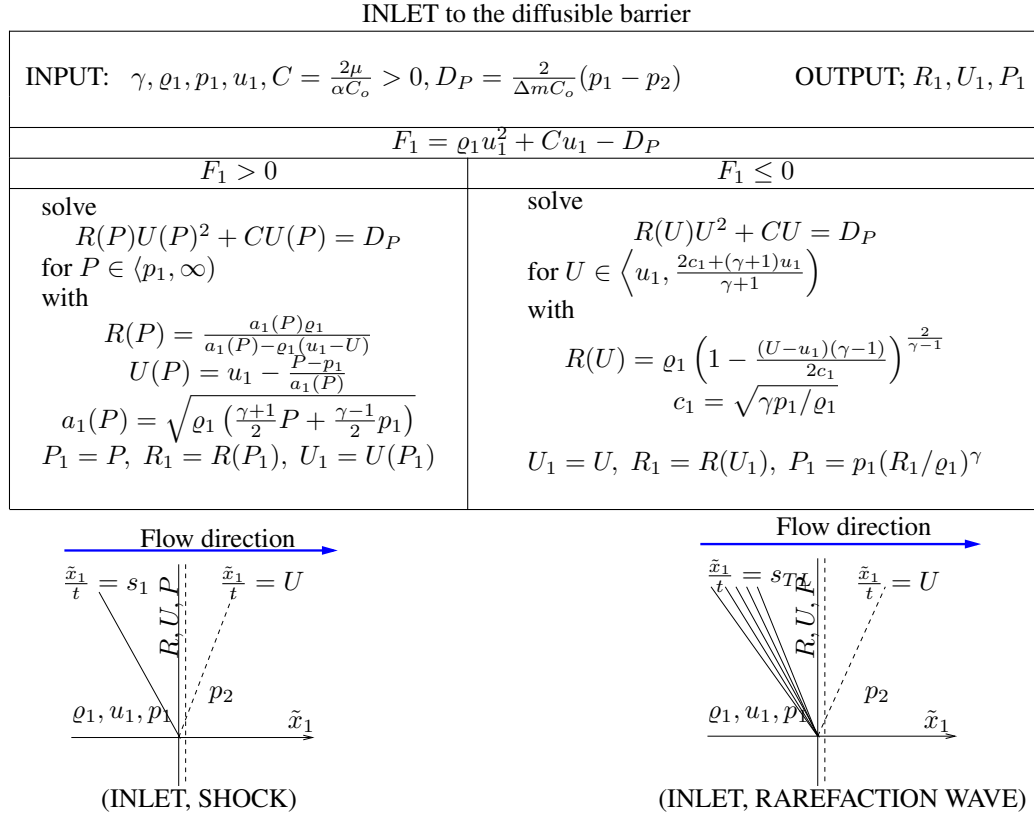


Fig. 2: Algorithm for the solution of the Problem 1 (INLET to the barrier). Both possibilities are taken into account.

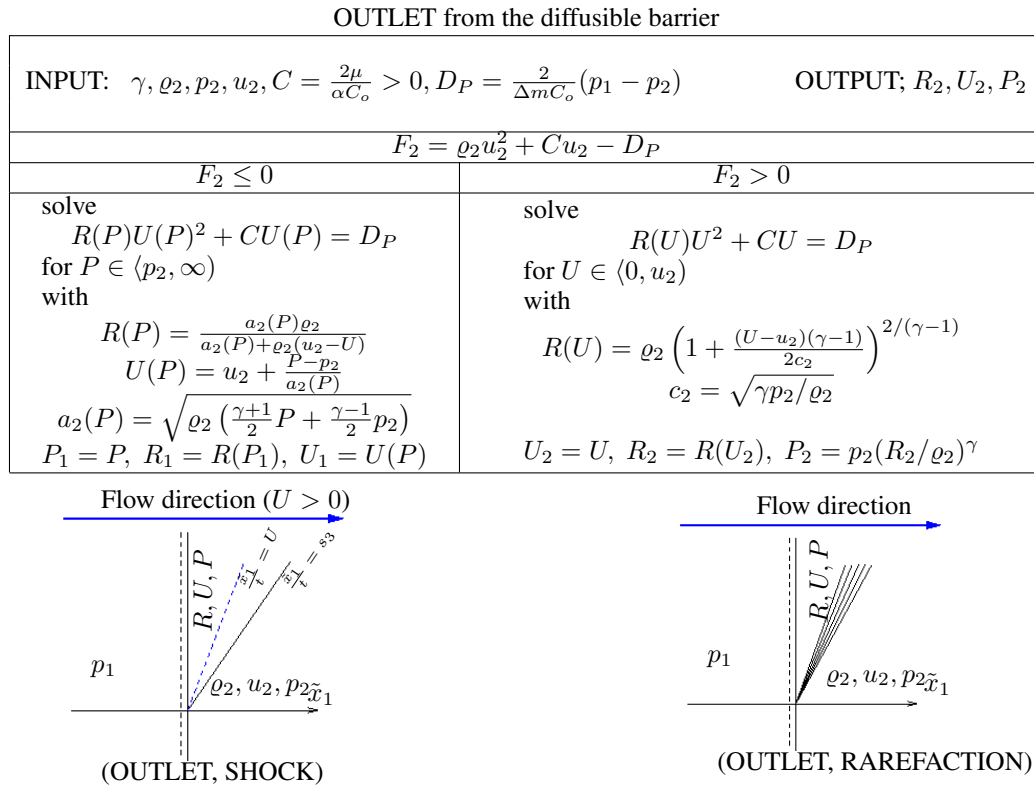


Fig. 3: Algorithm for the solution of the Problem 2 (OUTLET from the barrier). Both possibilities are taken into account.

5. Examples

The presented algorithm was implemented into the own-developed code, and used on the numerical examples. The Figures 4, 5 show the visual comparison of the flow through the diffusible barrier composed of multiple rigid plates, porous media, and the diffusible barrier. The velocity profiles at chosen vertical cuts are presented.

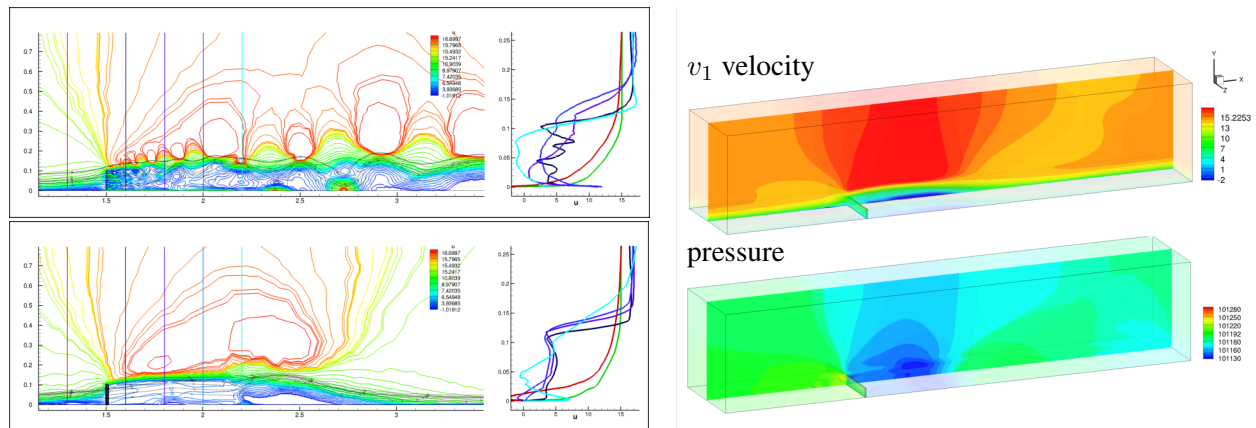


Fig. 4: Numerical simulation of the barrier composed of multiple plates, comparison with porous media, and 3D simulation. Regime $15[m s^{-1}]$, barrier height $h = 0.1 [m]$, results at the time instant $t = 0.2 [s]$.

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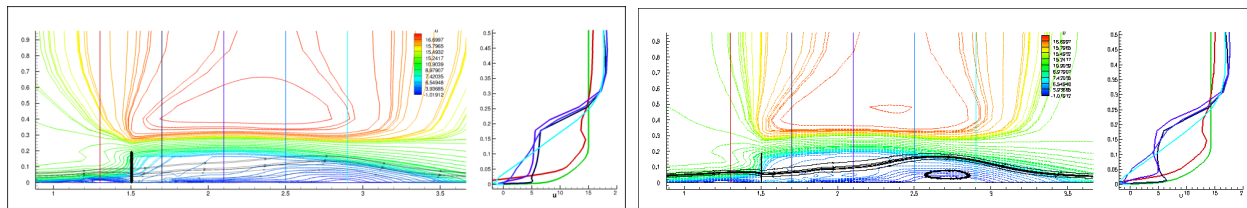


Fig. 5: Numerical simulation of the barrier simulated as porous media (left), and diffusible barrier (right).

6. Conclusions

The paper works with the compressible viscous gas flow, with the focus on the porous media and the diffusible barrier. The original boundary condition for the diffusible barrier (analyzed by authors also in Kyncl and Pelant (2013, 2017)) is presented, together with the computational algorithm. It is based on the analysis of the Riemann problem for the split Euler equations and the modifications of this problem. Here the left hand side initial condition is replaced by given complementary conditions. The resulting algorithm was implemented into the own-developed software, and used in numerical examples.

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