VELOCITY AND DIFFUSION ANALYSIS OF THE BINARY SPECIES INJECTED INTO THE AIR FLOW

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Abstract

The article deals with the qualification of non-reactive gas witch is injected into flowing air of the technological space. The considered gases are: helium and nitrogen N2. Their concentration in the air is measured in the outlet by stock testing indicator and indicates the velocity field in the technological space. The numerical analysis is used.

1 Introduction

The actual standard of computer art and software gives the possibility to solute structural, thermal and stress-strain tasks and also tasks of mass transfer joined with diffusion phenomenon. Creating the suitable computer model and using it in the environment of the special software products we get the results which allows us specify the selection for the next step by the design of the engineering project. In the form of model task there is predicted the air velocity field and the gas volume fractions, which are injected into the air flow injected. This process results into the selection of the gas which would be the most suitable for the project.

Symbols and bookmarks

x, y, z	rectangular coordinates	[m]
T	thermodynamic temperature	[K]
t	time	[s]
w	species velocity	[m.s-1]
ρ	mass density	[kg.m-3]
$\mathbf{R}$	unit acceleration vector $(\mathbf{R} = \mathbf{R}_x\mathbf{i} + \mathbf{R}_y\mathbf{j} + \mathbf{R}_z\mathbf{k})$	[m.s-2]
$\mathbf{r}$	position vector, $(r = xi + yj + zk)$	[m]
p	pressure	[Pa]
ν	kinematic viscosity	[m2.s-1]
G	mass fraction flux	[kg.m-2.s-1]
D_{AB}	binary mass diffusion coefficient	[m2.s-1]
x	mass fraction species	[kg.kg-1]
S_c	Schmidt number	[-]
V	volume fraction species	[kg.m-3]
M	molar mass	[kg.mol-1]
Q	volume rate	[m3.s-1]

Indexs

ref	reference	pr	pressure above outlet pressure
A	species A	B	species B
0	state at 0 sek	dif	diffuse
conv	conveyed	Hamilton operator	∇
s	species		

2 Model task

In the technological space sized $10 \times 10 \times 10$m flows the air with the volume rate 4000m^{3}h^{-1}. The air enters through the inlet opening sized $1,2 \times 10$m. Temperature of the air is 553K. Gas is injected to the flowing air with the volume rate 15m^{3}h^{-1}. Two types of non-reactive injected gases are taken in account, helium He and nitrogen N_2.

2.1 Teoretical basis

We consider the process goes under the atmospheric pressure. Gases in the technological space are homogeneous mediums, compressible and with the inner friction (viscosity). Velocity field is the result of the solution of the momentum balance defined by the Navier-Stockes diferential equation used for transient and laminar flow.

$$\frac{\partial \mathbf{w}}{\partial t} + \mathbf{w} \cdot \nabla \mathbf{w} = \mathbf{R} - \frac{1}{\rho}\nabla p + \nu(\Delta \mathbf{w}) \tag{1}$$

For flow of the real and compressible fluid with the conventional mass transfer we take a equation.

$$\frac{\partial \rho}{\partial t} + \mathrm{div}(\rho w) = 0 \tag{2}$$

Total pressure of the gas mixture is defined by Dalton law

$$p = p_A + p_B. \tag{3}$$

Pressure field in the investigated space is solved by equation.

$$p_{abs} = p_{ref} + p_{pr} + \rho_0(\mathbf{R} \cdot \mathbf{r}). \tag{4}$$

The rate equation for mass diffusion and for the transfer of species A in a binary mixture of A and B is expressed in form as.

$$G_{dif,A} = -\rho D_{AB} \nabla x_A. \tag{5}$$

The absolute flux of pieces A is the superposition of the mass diffusion and convective mass transfer [1].

$$G_A = G_{dif,A} + G_{conv.A} = -\rho D_{AB} \nabla x_A + x_A(G_A + G_B) \tag{6}$$

The distribution of the concentration species A in time and space we explain by using the II. Fick' law. The pieces in the process are without homogeneous chemical reactions. The II. Fick' law we take in form as.

$$\frac{\partial(\rho x_A)}{\partial t} + \nabla(\rho x_A w) + \nabla(\rho D_{AB} \nabla x_A) = 0 \tag{7}$$

Mass diffusion coefficient for the binary mixture of two gases is obtained from the Schmidt number Sc;

$$Sc = \frac{\nu}{D_{AB}} \tag{8}$$

From the experimental results of binary mixture for the diffusion coefficient follows the formula in form [1].

$$D_{AB} = \frac{p_0}{p} \left(\frac{T}{T_0} \right)^m D_{AB,0} \tag{9}$$

The exponent $m = 1,8$; $D_{AB,0}$ is defined for $T_0 = 273,15$K and $p_{ref} = 0,1013$MPa. For gases in the air diffused under normal conditions specifies [1], $(Sc)_0 = 0,6$. The volume (V_i) and mass (x_i) fraction relationship for the i-species is

$$V_i = \frac{\frac{x_i}{M_i}}{\sum \frac{x_i}{M_i}} \tag{10}$$

3 The simulation conditions

3.1 Geometrical model

Geometrical model is considered as the two-dimensional task in the co-ordinate system x, y. Model width is $x = 10$m and height is $y = 10$m, Fig. 1. The air inlet area is on the left side of the model in the height 3m above the floor area. The air outlet is situated in room ceiling 0.5m on the right-side of the room. The width of the outlet area is 1.2m too. Injected gasses are conveyed into the space through the opening in the height 0.05m situated over the air inlet. The model considers longitude of the openings (10m), equal to the space depth.

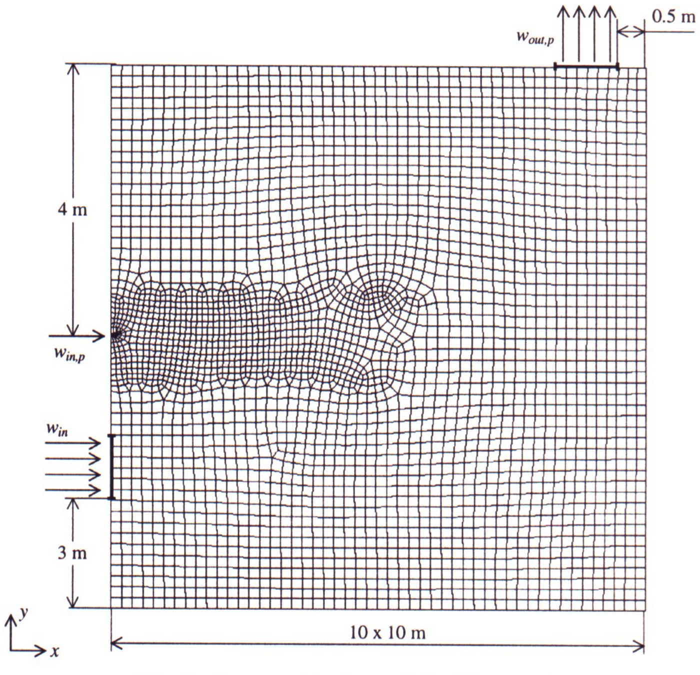

Figure 1: Geometrical model of the task

Thermophysical properties of species by temperature 553 K

Species	Dynamic viscosity $\eta \cdot 10^7 [\mathrm{Ns \cdot m^{-2}}]$	Mass dendity $\rho [\mathrm{kg \cdot m^{-3}}]$	Sc $[-]$	Diffusion coefficient $A_{AB} [\mathrm{m^2 \cdot s^{-1}}]$	Molar mass $M [\mathrm{kg \cdot kmol^{-1}}]$
Helium He	301.5	0.0905	0.17	0.001943	4.002
Nitrogen N_2	274.7	0.6124	0.17	0.000264	28.016
Oxygen O_2	324.0	0.6998	0.17	0.000272	32.000
Air	288.4	0.6329	0.17	0.000268	28.960

3.2 Thermophysical properties

The species are accepted as isotropic. The values of thermophysical properties are chosen from [2, 5]. They are prepared with the equations (8) a (9) and presented in Tab 1.

3.3 Boundary conditions

The air inlets into the technological space with steady-stated speed $w_{in} = 0.1 \mathrm{m \cdot s^{-1}}$. The species are injected into the space with steady-stated speed $w_{in,s} = 0.0083 \mathrm{m \cdot s^{-1}}$.

The velocity of the gas mixture on the volume boundary is $0.0 \mathrm{m \cdot s^{-1}}$. The outlet pressure above atmospheric used in model task is 0.0 Pa.

Species flow is laminar and adiabatic. Numerical analysis accepts influence of buoyancy force on flowing gases (the gravitational acceleration is considered).

3.4 Initial conditions

For time $t = 0$ the air velocity field in the space is taken from steady-state analysis (Fig. 2). In time 0 sec. gas begins to flow into the space (helium or nitrogen). The space volume is filled in with the air which is composed of 23,2 % oxygen mass fraction and 76,8 % nitrogen mass fraction.

3.5 Interpretation code

The model task is solved by FEM-method with program code ANSYS 5.5.3 - FLOTRAN-CFD. Type element FLUID 141 is used. It is two-dimensional quadrilateral element with six degrees of freedom: velocity, pressure, temperature, turbulent kinetic energy, turbulence dissipation rate, mass fraction of species (max. 6 species). Task analysis is linear and transient.

4 Analysis results

4.1 Steady-state air velocity field

Air flowing in the investigated space is independent on time and its velocity field is presented on Fig. 2. In this air velocity field the locality with the convectional acceleration is dominated and air speed is increasing there (node K neighbourhood). In the other two localities with the whirlpool in the flow the velocity in nodes L and M is near the zero. The maximal air flow velocity is $w_{max} = 0.110\text{m} \cdot \text{s}^{-1}$ in the node K $(x = 3.857\text{m}, y = 4.474\text{m})$. The minimal $w_{min} = 0.0007\text{m} \cdot \text{s}^{-1}$ is in the node L $(x = 3.791\text{m}, y = 7.596\text{m})$.

The velocity profile of the flow in outlet (nodes c, d) has maximal speed value $0.093\text{m} \cdot \text{s}^{-1}$ and average value $0.071\text{m} \cdot \text{s}^{-1}$, Fig. 3.

Pressure course (above the pressure in outlet) between nodes a, b achieves maximal pressure 0.001173 Pa, Fig. 4. The average pressure is 0.000678 Pa.

The check of the results correctnes is done by using the law of mass balance. Difference between air mass rate on inlet and on outlet is obtained from average velocities and pressures on base equation for steady-state isothermal fluid flows [4]. Result of the check account shows that the mass flow rate in the outlet is $3,6\%$ higher than the mass flow rate in inlet. The predicated velocity field is solved with sufficient correctness.

4.2 Helium injection

Behaviour results of the investigated air-helium system are two parameters: a) transient mass fraction field of helium in the technological space, b) time dependent changing of the helium volume concentration in the air in outlet. Fig. 5 shows distribution field of the helium mass fraction in the flowing air diffused in the times: 50 s, 250 s and 2500 s. Volume fractions of helium in outlet are calculated by equation (10) and are presented in Tab. 2. The average values of the volume fraction are recorded in form temporal function. Maximal values of the helium volume fraction in the flowing mixture in outlet are presented for the better illustration. In Fig. 5 the graph of the maximal and average helium volume fraction as the time function is shown.

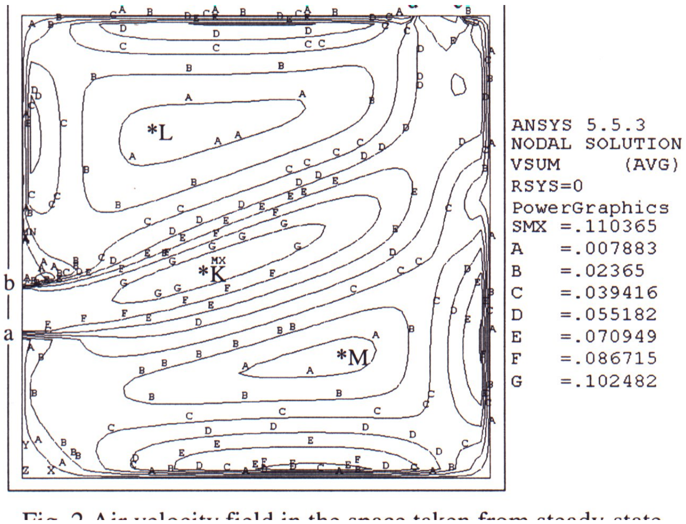

Figure 2: Air velocity field in the space taken from steady-state analysis, $[\mathrm{m} \cdot \mathrm{s}^{-1}]$

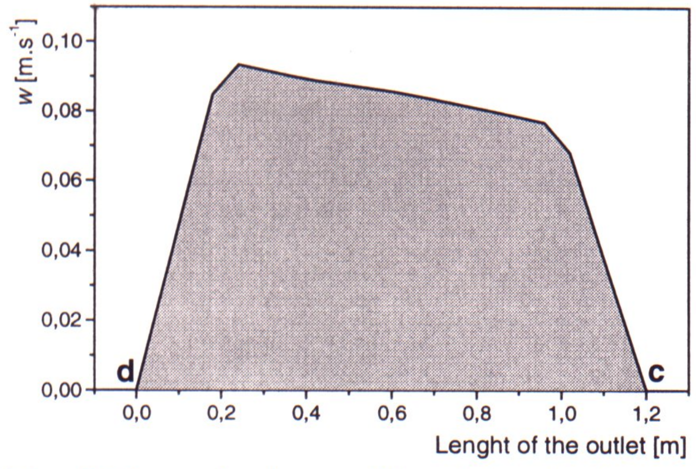

Figure 3: The velocity profile of the air flow in outlet

Helium volume fractions in outlet

Helium volumen rate He, $\dot{Q} = 15\mathrm{m}^3 \cdot \mathrm{hod}^{-1}$								
Time [s]	0	50	150	250	500	1000	1500	2500
Volume fraction [%] (average value)	0	0.449	0.508	0.608	0.710	0.739	0.740	0.740
Volume fraction [%] (maximal value)	0	0.451	0.533	0.657	0.771	0.802	0.804	0.801

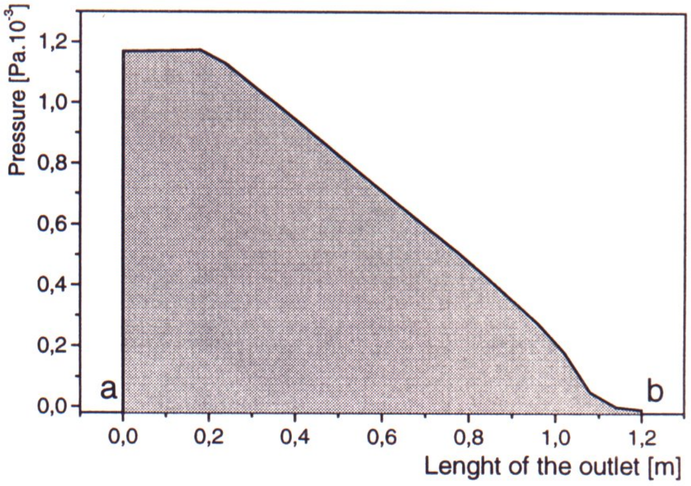

Figure 4: Pressure course in intlet

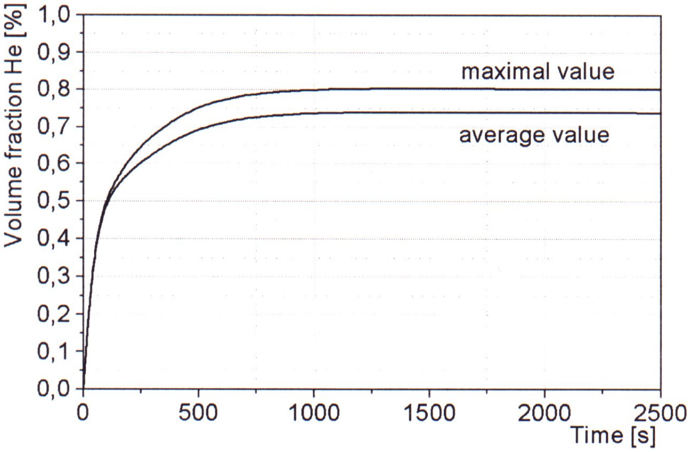

Figure 5: Maximal and average helium volume fraction as the time function He [%]

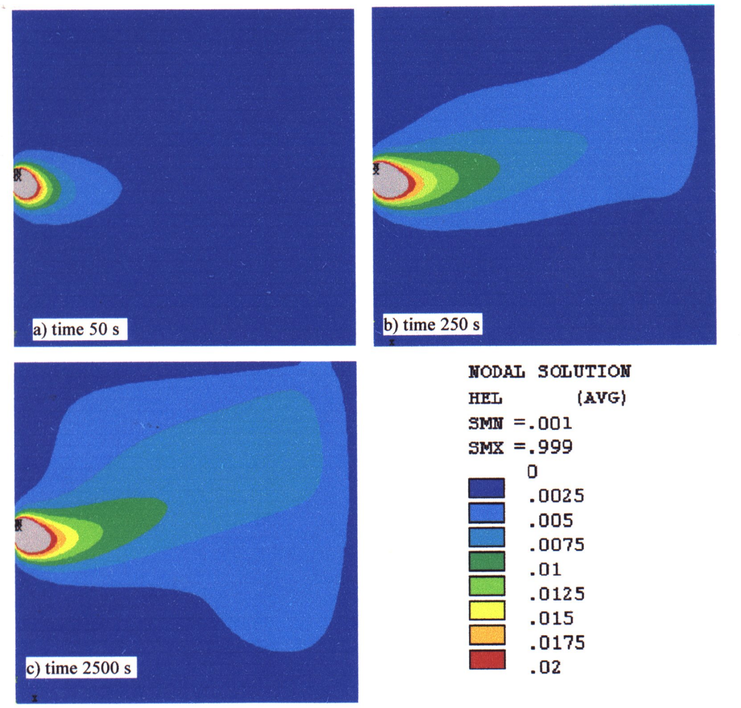

Figure 6: The helium mass fraction field $[\mathrm{kg} \cdot \mathrm{kg}^{-1}]$ in time, a) 50 s, b) 250 s, c) 2500 s.

Oxygen volume fraction in outlet

Nitrogen volumen rate, $\dot{Q} = 15\mathrm{m}^3 \cdot \mathrm{h}^{-1}$								
Time [s]	0	50	150	250	500	1000	1500	2500
Volume fraction [%] (average value)	20.720	20.719	20.708	20.688	20.668	20.664	20.664	20.664
Volume fraction [%] (minimal value)	-	20.718	20.700	20.669	20.639	20.633	20.631	20.631

4.3 Nitrogen injection N_2

The second alternative of the model task is the nitrogen injection. Soluted objects are the change (decrease in value), mass (volume), oxygen fraction in outlet, and prediction of the transient nitrogen mass fraction in the flowing air. The numerical analysis results are shown in Fig. 7, graphical dependancy in Fig. 8 and in Tab. 3. Fig 7 shows distribution field of the oxygen mass fraction in the flowing air diffused in the times: 50 s, 250 s and 2500 s. The average time dependent value of the oxygen O_2 volume fraction is presented in Fig. 8. The minimal value of the oxygen volume fraction is also presented. The oxygen volume fraction in outlet is calculated by equation (10) and the results are declared in Tab. 3.

5 Conclusion

The velocity and diffusion analysis of the injected gases helium and nitrogen into the steady-state air flow in the model task shows:

1. The steady-state concentration of injected gases is attained in time 900 s.

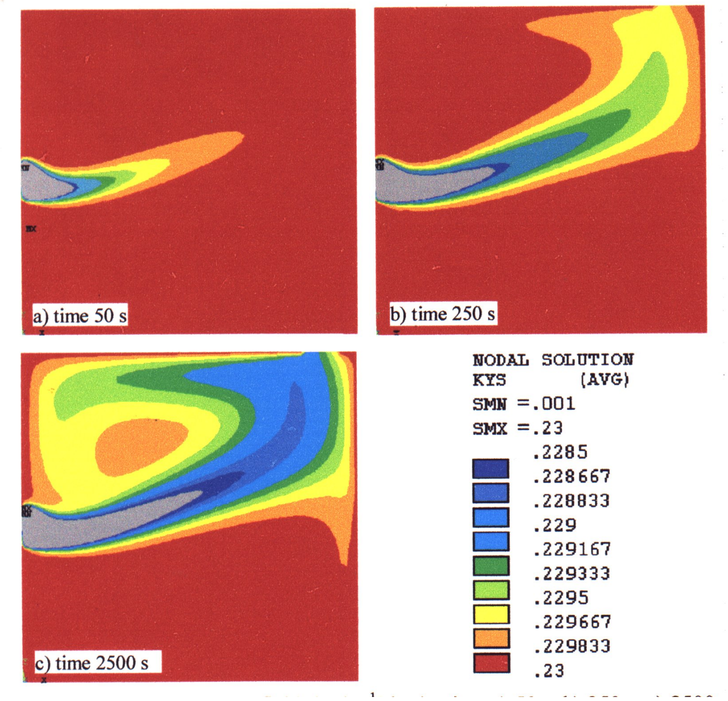

Figure 7: Oxygen mass fraction field $[\mathrm{kg} \cdot \mathrm{kg}^{-1}]$ in the time a) 50 s, b) 250 s, c) 2500 s.

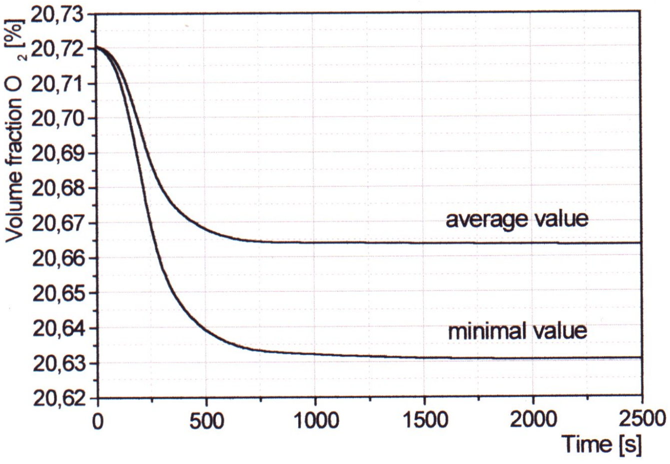

Figure 8: Average and minimal oxygen volume fraction O_2 [%] as the time function

2. The diffusion coefficient of helium is higher than the nitrogen coefficient. This fact explains higher mass diffusivity of helium in the relation to conveyed mass flux.
3. Conveyed mass flux dominates in injection of the nitrogen.
4. The helium volume diffusion fraction in outlet fluctuate from 0.0 % to 0.8 %.
5. The injection of the nitrogen decreases the oxygen concentration in outlet in non-essential rate. The volume fraction is in interval from 20.720 % to 20.631 %.
6. The helium and oxygen volume fraction in the outlet area are non-homogenous.
7. The influence of the buoyancy force on helium particles is not significant. These results represent, that helium will be not accumulated under the space ceiling.
8. For the considered task the injected volume rate of nitrogen $\dot{Q} = 15\mathrm{m}^3 \cdot \mathrm{h}^{-1}$ is unsatisfying.

Practical exploitation velocity and diffusion multiple species analysis results show that the indirect method for the flow monitoring is possible. The variation of the helium concentration in outlet is sufficient for the measuring with the stock testing indicator.

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