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Helium flow distribution problem on example of exhaust channel simulation

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Introduction

This work covers the actual problem of design and maintenance of complex hydraulic systems (or pipeline network), which play very important role in the life of mankind. People use given systems for oil and gas transportation, water and heat supply in the cities, irrigation etc. Hydraulic system is defined as a set of different facilities (pump stations, pressure regulators, shutters etc.) and connecting them pipelines, closed or open channels involved in the transportation of compressible and incompressible fluids (water, oil, gas etc.)[1].

Hydraulic systems are a well known example of a complex and large scale distributed parameter system. By this reason the modeling approaches, numerical methods and optimization of operating modes of fluid transport networks are of permanent interest for researchers and engineers who create more and more perfect simulators. But all these simulators have common concepts of graph representation of hydraulic network, which appeared several decades ago at the inception of the theory of hydraulic circuits.

In this work author considers the problem of helium flow distribution on example of simulation of exhaust channel in the developed SMTVSS simulator

Flow Distribution Problem

Hydraulic system is a set of connected components with different geometry: bends, expansions, valves. Total pressure losses caused by given components in pipe is usually estimated using equation of the form:

$$P^* = \frac{S \rho u^2}{2}$$

where U - velocity of flow, ρ - density of fluid, S - hydraulic resistance coefficient which depends on the type of component geometry. Equations and values of this coefficient for different model components can be found in literature [2].

Hydraulic system can be represented by graph, in which nodes represent connections between components; edges are geometrical interpretation of components. Nodes hold information only about pressure distribution in the hydraulic system, edges contain all other information about model state: temperature, flow rate, pressure drop and other properties in the system.

The matrix, associated with topology representation of graph G having n vertices $v_1, v_2 \ldots v_n$ and m edges $e_1, e_2 \ldots e_m$ is the **incidence matrix** A_{mn} in which each element a_{ij} is represented by:

$$A = \{a_{ij}\} = \begin{cases} 1, \text{ if } v_i \text{ - target of } e_i \\ -1, \text{ if } v_i \text{ - source of } e_i \\ 1, \text{ otherwise} \end{cases}$$

To describe flow in the hydraulic system following laws are used:

1. The first Kirchhoff's law, describing local **mass conservation law** of fluid flow for each node can be easily represented by using incidence matrix:

$$AG = 0$$

where G - flow rate that is defined by following formula:

$$G(P,T,U,F) = \frac{P^* F \frac{U}{\sqrt{k(P,T)R(P,T)T}}}{\sqrt{R(P,T)T^*}} \sqrt{k(P,T)\left[\frac{2}{2+(k(P,T)-1)\left(\frac{U}{\sqrt{k(P,T)R(P,T)T}}\right)^2}\right]^{\frac{k(P,T)+1}{k(P,T)-1}}}$$

where P^* - total pressure or stagnation pressure defined by pressure P:

$$P^*(P,T,U) = P\left(1+\frac{k(P,T)-1}{2}\frac{U^2}{k(P,T)R(P,T)T}\right)^{\frac{k(P,T)}{k(P,T)-1}}$$

and T^* - total temperature or stagnation temperature defined by temperature T:

$$T^* = T + \frac{U^2}{2c_p(P,T)}$$

k(P; T) - adiabatic index, R(P; T) - heat capacity difference, c_p - heat capacity, U – velocity of flow, F – cross sectional area.

2. Pressure drop law in the hydraulic system:

$$A^T P^* = \frac{S\rho U u}{2}$$

where U - diagonal matrix of velocities, u - vector of velocities, ρ - diagonal matrix of densities, S - diagonal matrix of hydraulic resistance coefficients.

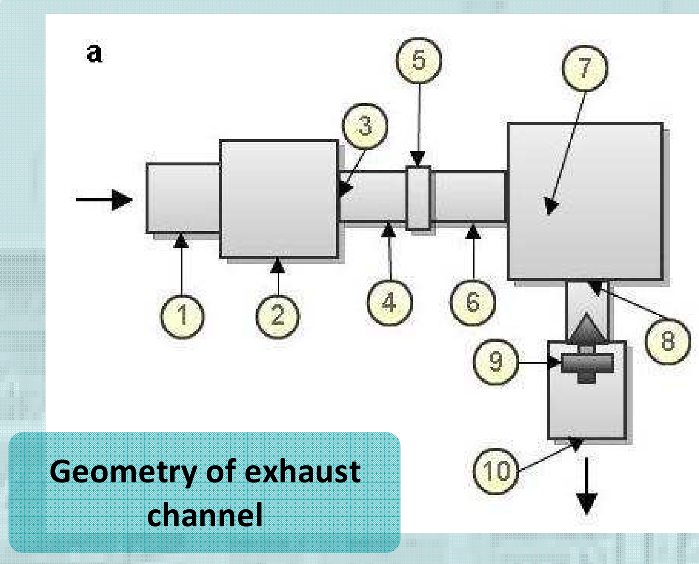
3. Energy conservation law is represented by T = const or in other words:

$$T^* - T^i - \frac{u^2}{2c_p(P,T)} = 0$$

Finally we get nonlinear system of equations:

$$\begin{cases} AG = 0 \\ A^T P^* - \frac{S\rho U u}{2} = 0 \\ T^* - T_i + \frac{U_i^2}{2c_{p_i}} = 0 \end{cases}$$

which is solved using Newton's method.



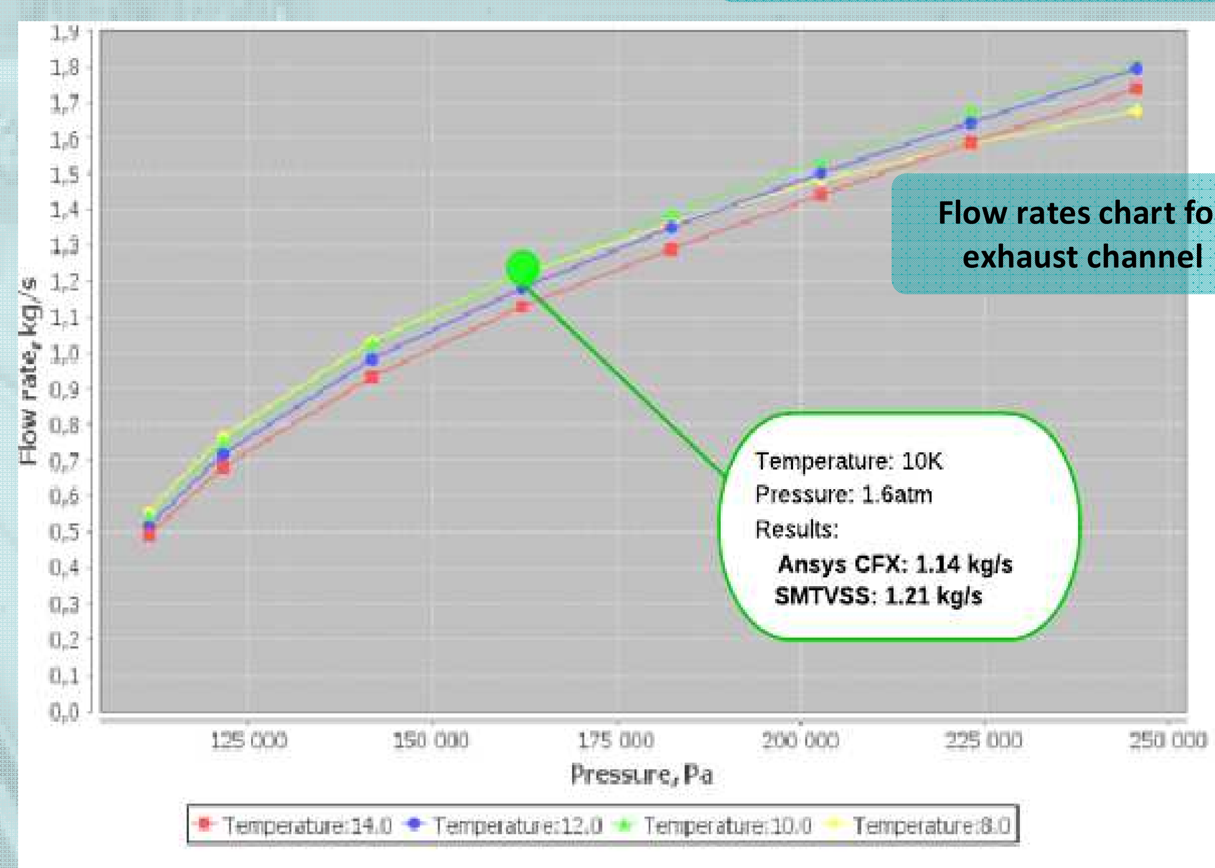
Geometry of exhaust channel

edge id	component	resistance	area
1	entrance	0.223	0.007
2	expansion + circular channel	0.11	0.022
3	transition	0.4	0.0021
4	circular channel	0.0616	0.0035
5	transition	0.5	0.0021
6	circular channel	0.1308	0.0035
7	expansion+ bend (90)	0.8321	0.0357
8	contraction	0.8	0.0056
9	shutter	0.11	0.0201
10	exit	0.21	0.0079

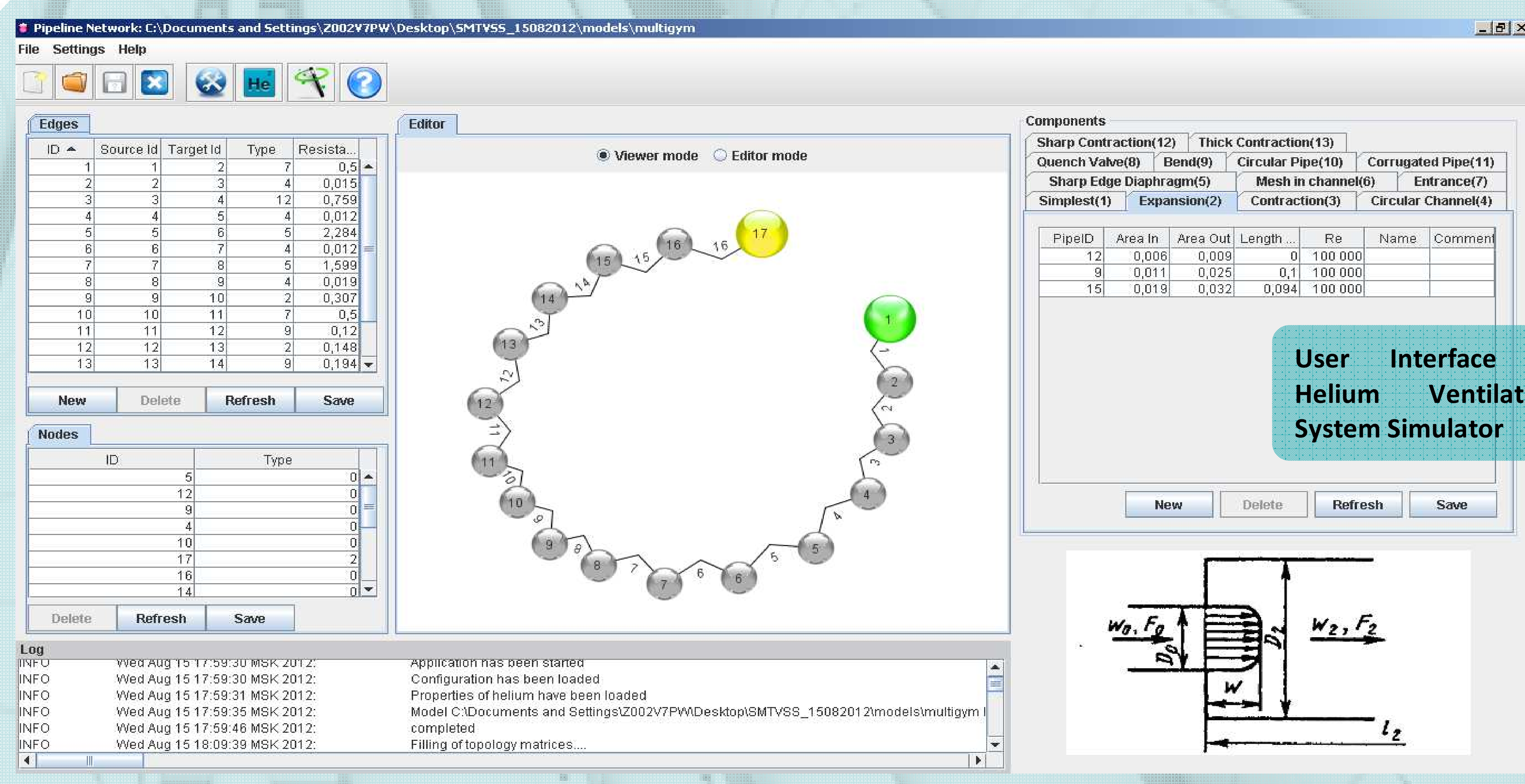
Parameters of hydraulic model used in calculation

edge id	density(CFX)	velocity(CFX)	density(VS)	velocity(VS)
4	6.87	59	7.38	62.77
9	5.86	41	5.84	48.61
10	5.20	17	5.10	13.94
11	4.16	30	4.41	35.99

Comparison of results calculated by SMTVSS and CFX

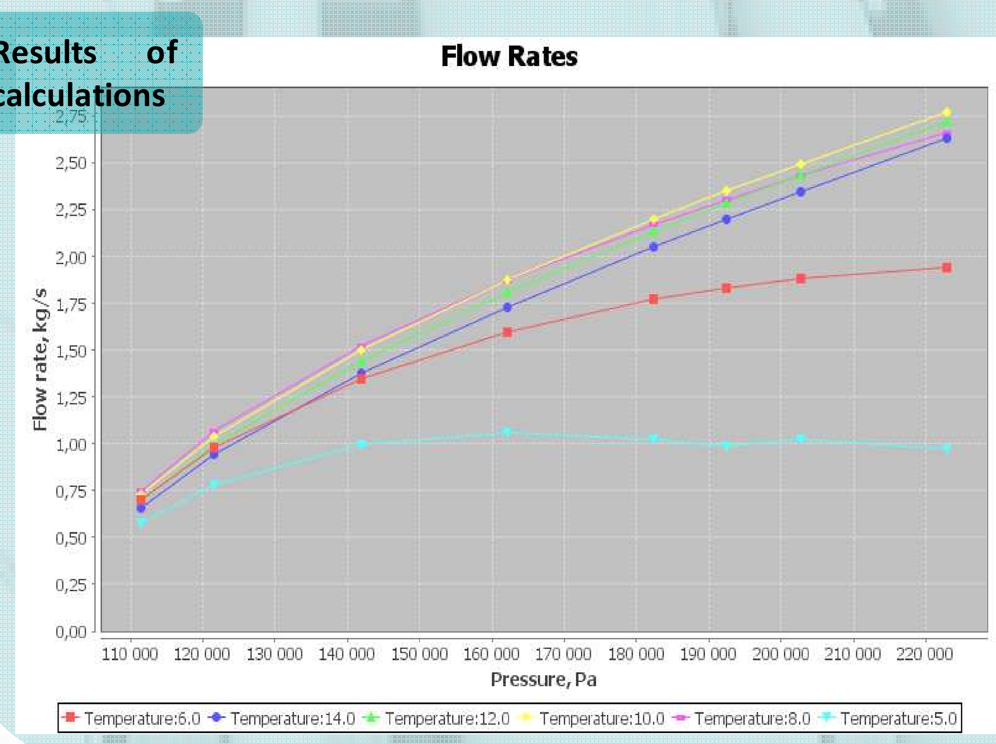


Flow rates chart for exhaust channel



User Interface of Helium Ventilation System Simulator

Results of calculations



Conclusions

It's to be noted that in spite of all simplifications which were used in numerical scheme and model of flow distribution the results obtained by SMTVSS well correspond to the reference points in the Ansys CFX model.

The model of flow distribution presented above is fit for helium flow speeds less than sonic speed and were tested for subsonic velocity range.

References

[1] Merenkov, A. and Hasilev, V., Theory of hydraulic circuits, Moscow: Nauka, 1nd edition,1985 - 276 p.

[2] I.E. Idelchik, Handbook of Hydraulic Resistance, Jaico Publishing House, 2005- 816 p.

"Modern Problems of Applied Mathematics & Computer Science"

August 22-27, 2012, Dubna, Russia