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Evaporator system of water desalination based on Ranque-Hilsch vortex effect

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Abstract

The vortex tube of the water desalination evaporator system is studied based on the Ranque-Hilsch vortex effect. Vortex effects mathematical model is based on Reynolds Equations which is completed by k-w SST turbulence differential model. One of the goals of the research is to define the geometry of the vortex tube scaled model. Another goal of the research is to define the input parameters for Reynolds Stress Turbulence Model. The results of the research are the defined optimal geometry parameters of the vortex tube prototype and input parameters required for Reynolds Stress Turbulence Model analysis.

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Keywords: Computational Fluid Dynamics, Ranque-Hilsch effect, vortex tube.

1. Introduction

Nowadays in Russia the desalted water is mainly produced using chemical demineralization. This technology is expensive, harmful for ecology and obsolete. The introduced design of the evaporator system allows the water desalination employing the intensified heat and mass processes in the centrifugal force field.

An effectiveness of the vortex tube operation depends on its design and operating parameters. Therefore, the key term of the vortex tube implementation is determination of its optimal design and operating parameters.

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For the numerical simulation of viscous turbulent flow of gas a mathematical model based on the system of Reynolds equations [1, 2] completed by k-ω SST turbulence differential model [3, 4].

2. Formulation of a problem

The main goal of the numerical simulation is to determine the geometric and technical parameters of the vortex tube evaporator water desalination, which are necessary for the design and further produce the prototype model of of evaporator system. The second goal is to determine the input parameters for numerical simulation with use mathematical model based on Reynolds Stress Turbulence Model.

Schematic drawing of the vortex tube is showed in Fig. 1. Vortex tube dimensions choosing according recommendations of [5] and summarized in tab. 1.

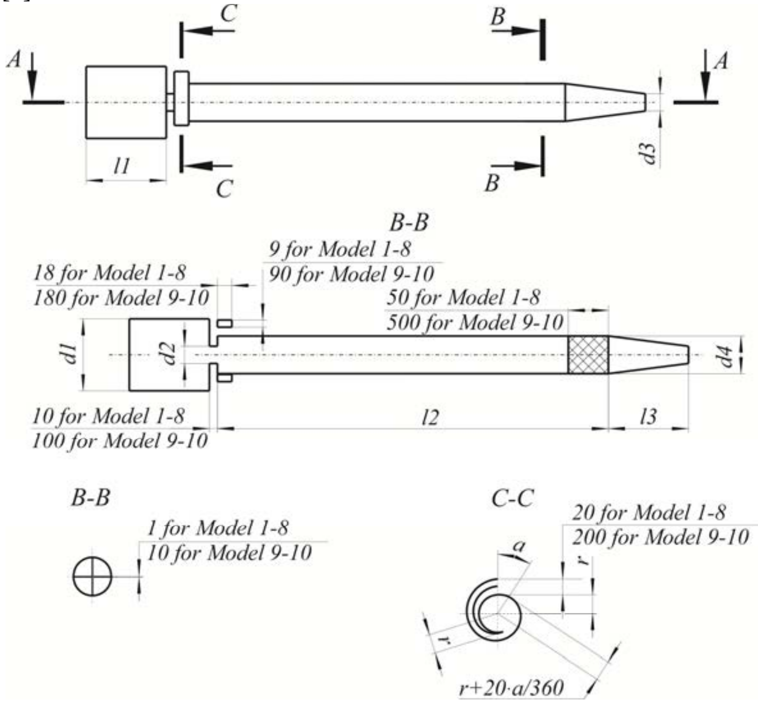

Fig. 1. Schematic drawing of the vortex tube.

Table 1. Dimensions of models.

Model name	L, mm	l3, mm	d1, mm	d2, мм	d3, mm	d4, mm
Model №1	488	50	60	13.5	6.75	21.6
Model №2	488	50	60	13.5	10.125	21.6
Model №3	488	50	60	13.5	13.5	21.6
Model №4	418	50	60	13.5	6.75	21.6
Model №5	488	50	60	21.6	21.6	47.1
Model №6	488	50	60	21.6	10.8	47.1
Model №7	418	50	60	13.5	6.75	21.6
Model №8	303	50	60	13.5	3	21.6
Model №9	3030	500	600	135	30	216
Model №10	3030	500	600	135	30	216

Models from 1 to 7 are prototype model which will be used in full-scale experiment for correction mathematic model of vortex tube of evaporator system of water desalination. Models 8, 9 and 10 are full-scale industrial models. Boundary conditions of mathematical model and their names is showed in Fig. 2. The numerical values of the physical parameters which set up at the boundaries conditions summarized in tab. 2 and 3. Thermophysical properties of vapor chosen in accordance with the recommendations [6, 7].

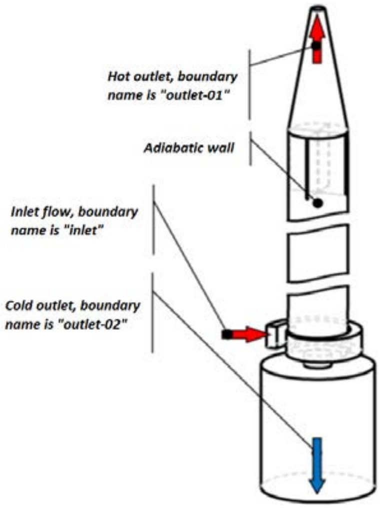

Fig. 2. Scheme of boundary conditions.

Table 2. Grid value and material of fluid.

Model name	Number of Elements in computing model	Fluid material
Model №1	640 742	Air
Model №2	653 580	Air
Model №3	657 833	Air
Model №4	604 087	Air
Model №5	826 909	Air
Model №6	817 558	Air
Model №7	4 852 368	Air
Model №8	4 212 802	Air
Model №9	4 212 802	Air
Model №10	4 212 802	Vapor

Table 3. Material properties.

Fluid material	T_{inlet} , K	$P_{outlet-01}$, $P_{outlet-02}$, Pa	μ, Pa·s	c_p, J/(kg·K)	λ,Wт/(m·K)	R, J/(kg·K)
Air	373.15	-9700	$1.83 \cdot 10^{-5}$	1004.4	0.0261	287
Vapor	373.15	-9700	$1.85 \cdot 10^{-4}$	2042.0	1.4000	461

T_{inlet} – fluid temperature in inlet;
$P_{outlet-01}$ – reference pressure of fluid in outlet-01;
$P_{outlet-02}$ – reference pressure of fluid in outlet-02;
R – gas constant for state equation;
c_p – specific heat capacity for constant pressure;
λ – thermal conductivity;
μ – dynamic viscosity.

3. Mathematical model

For the numerical simulation of vortex flow used Reynolds Averaged Navier-Stokes equations (RANS) [1, 4, 8] closed by two-equation k-ω SST turbulence energy model [3, 4, 8].

The solution of the Reynolds Averaged Navier-Stokes equations (RANS) closed by two-equation k-ω SST turbulence energy model was using program DinamLGTM [10] which based on control volume approach [9].

4. Results of numerical simulation

Schematic eddy generation in vortex tube for models 6, 7 and 9 is shown in Fig. 3. These eddy generation is typical for all considered flows. Fig. 3 is shown separated on cold flow and hot flow according Ranque-Hilsch effect.

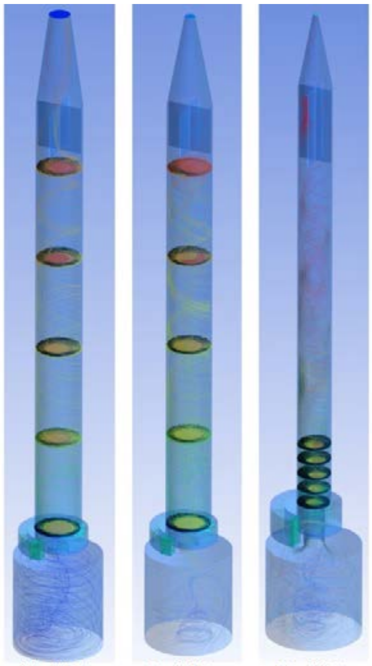

Fig. 3. Scheme of eddy generation in vortex tube.

The main goal of the calculations is the choice of optimal geometric parameters of the prototype. The results of the calculations for all cases are summarized in table 4.

The main characteristic of the quality of the process of desalination is ratio of mass flow of hot gas to mass flow of cold gas, which advises boundary condition “outlet-01” and “outlet-02”, Fig. 2. The model 1 to 4 has the same structure partitioning the computational domain into control volumes. The difference between models was only in geometry. As shown by calculations, the most successful geometric dimensions model is model 4, Fig. 4-a.

Models 5 and 6 differ from models 1 to 4 the increased volume inner section of tube where reduce (generate) vortex flow. The model 6 has productivity by 4 times less than the model 4, Tab 4, Fig. 4.

Model 4 and 7 differ in the quality of approximation of the computational domain. The number of control volumes of the computational domain differs by 6 times (tab. 2). The summarized time of the calculation for the model 4 is 10 hours and for model 7 is 0.8 hours. On structurally stable grid (coarse mesh) more comfortable to make a preliminary calculation and the next step is use of fine mesh for refinement parameters of calculation model. Comparison results of calculation showed that the grinding significantly affects the final results and for similar vortex flow necessary to carry out the analysis grid independence for all models, Fig. 4-b. The influence of the length of inner section of tube where reduce (generate) vortex flow is showed comparing model 7 and model 8 (model 8 shorter on 30% then model 7). Results of calculation between model 7 and model 8 the similar (tab. 4, fig. 5-a), but length of inner section of tube model 8 shorter on 30%. Model 8 is more compact and is preferable for manufacture of the prototype model.

Model 8 and model 9 different by scale, model 9 is 10 times more model 8. Scale vortex structures formed in the volume inner section of tube are substantially different, as the transition from air to vapor (Fig. 5-b).

Table 4. Results of numerical simulation.

Model name	Inlet Velocity, m/s	Inlet Pressure, bar	Ratio of the mass hot flow and cold flow	Difference between hot flow temperature and cold flow temperature, K	Average reference pressure in domain, bar	Mass flow of gas (vapor), kg/s	Volume-flow rate of gas (vapor), l/min
1	100	0.09	6.9	7.1	-0.05	0.01644	818.5
1	150	0.53	7.7	31.9	0.09	0.03468	1727.0
1	200	1.52	8.0	63.5	0.37	0.07610	3789.2
1	250	3.65	9.2	104.1	0.96	0.17549	8738.1
2	100	0.09	11.1	7.1	-0.05	0.01645	818.9
2	150	0.54	9.8	28.5	0.07	0.03497	1741.5
2	200	1.77	7.4	65.0	0.40	0.08370	4167.4
2	250	6.06	7.5	109.3	1.51	0.26651	13270.2
3	100	0.001	30.0	1.1	-0.14	0.01513	753.4
3	150	0.41	20.3	11.7	0.00	0.03191	1588.7
3	200	1.70	12.0	49.7	0.32	0.08153	4059.6
3	250	8.07	10.0	122.0	1.85	0.34243	17050.5
4	100	0.09	6.8	7.1	-0.05	0.01642	817.5
4	150	0.56	6.2	32.7	0.09	0.03536	1760.4
4	200	1.73	6.1	69.1	0.41	0.08249	4107.2
4	250	4.46	5.1	110.3	1.11	0.20614	10264.2
5	100	-0.04	1500	-0.8	-0.09	0.01443	718.6
5	150	0.02	316.4	0.6	-0.08	0.02312	1151.2
5	200	0.16	192.2	3.4	-0.07	0.03504	1744.8
5	250	0.43	111.2	1.5	-0.05	0.05418	2697.8
6	100	-0.04	22.9	0.4	-0.09	0.01453	723.7
6	150	0.05	21.3	3.0	-0.08	0.02375	1182.8
6	200	0.20	18.4	8.4	-0.05	0.03614	1799.5
6	250	0.56	22.6	21.6	0.01	0.05903	2939.3
7	100	-0.04	22.9	0.4	-0.09	0.01453	723.7
7	150	0.05	21.3	3.0	-0.08	0.02375	1182.8
7	200	0.20	18.4	8.4	-0.05	0.03614	1799.5
7	250	0.56	22.6	21.6	0.01	0.05903	2939.3
8	100	0.06	13.3	5.1	-0.07	0.01601	797.1
8	110	0.14	16.2	10.3	-0.04	0.01896	944.3
8	120	0.26	28.0	15.4	-0.01	0.02283	1136.5
8	130	0.33	27.0	17.8	0.00	0.02605	1297.3
8	140	0.40	26.4	20.7	0.02	0.02952	1469.8
8	150	0.47	27.1	24.5	0.04	0.03331	1658.6
9	100	0.06	12.8	4.1	-0.07	1.59833	79585.0
9	120	0.24	47.1	10.1	-0.03	2.24131	111600.7
9	150	0.46	48.2	21.1	0.02	3.29885	164258.0
10	100	0.34	26.5	3.1	0.00	1.27337	63404.4
10	120	0.79	17.2	11.5	0.14	2.03187	101171.7
10	150	1.42	17.1	17.2	0.29	3.43358	170966.5

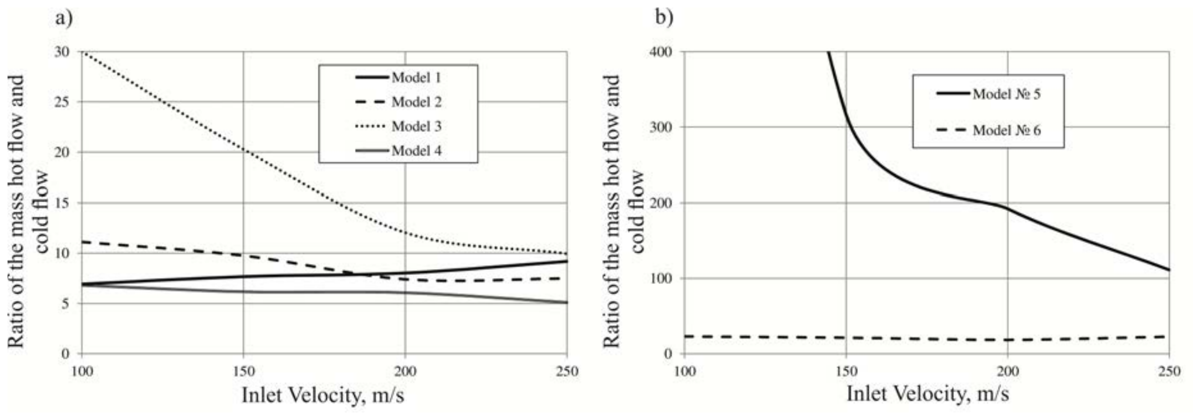

Fig. 4. Ratio of the mass hot flow and cold flow (a) for models 1 to 4; (b) for models 5 and 6.

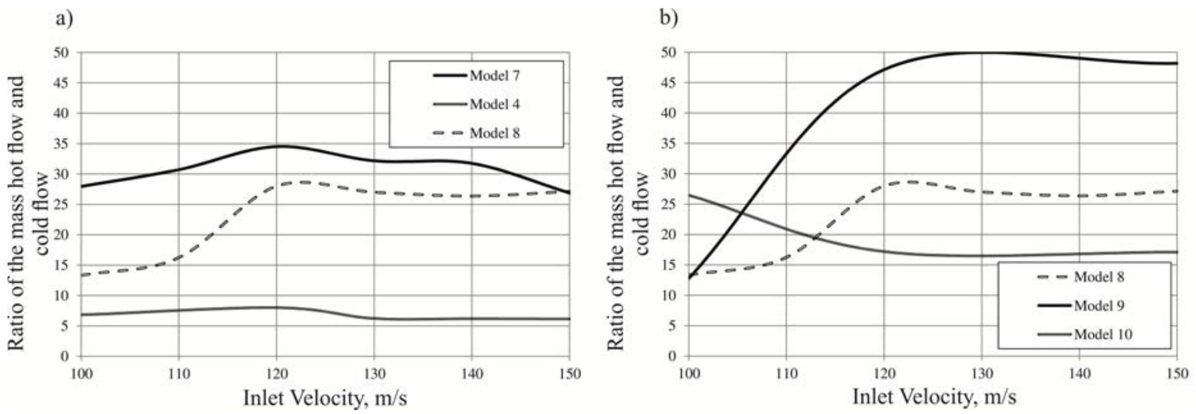

Fig. 5. Ratio of the mass hot flow and cold flow (a) for models 4, 7 and 8; (b) for models 8 to 10.

5. Conclusion

For manufacture prototype according calculations more reasonable is model 8, which is scaled-down industrial model 10. Manufacture of prototype and running of physical experiment for air make more precise setup calculation with use Reynolds Stress Turbulence Model.

Analyzing of vortex in the tube of evaporator water desalination with appear separation flow according Ranque-Hilsch effect for Reynolds Stress Turbulence Model necessary make calculation with fine grid where minimal controls volume of domain will be 4.5 million. The next necessary condition for get reliable data is achieved grid independence. This work is planned to be performed at the next step of calculations.

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