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DEVELOPMENT OF AN ENVIRONMENTALLY FRIENDLY STEAM TURBINE WORKING ON ORGANIC FLUID FOR WASTE HEAT UTILIZATION

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РАЗРАБОТКА ЭКОЛОГИЧЕСКИ ЧИСТОЙ ПАРОВОЙ ТУРБИНЫ НА ОРГАНИЧЕСКОМ РАБОЧЕМ ТЕЛЕ ДЛЯ УТИЛИЗАЦИИ ВТОРИЧНОЙ ТЕПЛОВОЙ ЭНЕРГИИ

This article discusses the waste heat utilization technology of various industries, by steam-turbine installations working by an organic Rankin cycle. Application of this technology allows making the electric power without any fuel expenses which allows to decrease the relative emission of production pollution, to decrease the environmental heat pollution and to increase the efficiency of fuel usage in the main production. As an example, the study presents a calculation of the potential of waste heat utilization for the PAO «Gazprom» gas transmission network, which amounts to 3,9 GW, allowing to reduce the relative emission of production pollution by 25 %. The article also offers information about the 560 kW organic turbine design and the problems of experimental research.

STEAM TURBINE; ORGANIC RANKINE CYCLE; HEAT UTILIZATION; EMISSION; HARMFUL EMISSIONS; ENERGY EFFICIENCY; ORGANIC FLUID; HEXAMETHYLDISILOXANE.

В представленной статье рассматривается технология утилизации теплоты выхлопных газов термических агрегатов различных отраслей промышленности с использованием паротурбинных установок, работающих по органическому циклу Ренкина. Применение подобной технологии позволяет вырабатывать электроэнергию без дополнительных топливных затрат, что приводит к снижению относительной эмиссии вредных веществ основного производства, уменьшает тепловое загрязнение окружающей среды и, таким образом, приводит к росту эффективности использования внутренней энергии топлива, потребляемого на основном производстве. В качестве примера выполнен расчет использования потенциала теплоты уходящих газов газоперекачивающих агрегатов газотранспортной сети ПАО “Газпром”, суммарная мощность которых составляет 3,9 ГВт. Показано, что возможно сократить удельную эмиссию вредных веществ на 25 %. В статье также представлена информация о разрабатываемой утилизационной органической паровой турбине натурной мощностью 560 кВт и проблемах экспериментальных исследований данной турбины.

ПАРОВАЯ ТУРБИНА; ОРГАНИЧЕСКИЙ ЦИКЛ РЕНКИНА; УТИЛИЗАЦИЯ ТЕПЛОТЫ; ЭМИССИЯ; ВРЕДНЫЕ ВЫБРОСЫ; ЭНЕРГОЭФФЕКТИВНОСТЬ; ОРГАНИЧЕСКАЯ ЖИДКОСТЬ; ГЕКСАМЕТИЛДИСИЛОКСАН.

Introduction

The intensive growth of modern industry, which using as the main energy source hydrocarbon fuel, leads to a direct increasing of pollution by exhaust gases. This article narrates conversion technology of medium and low-potential waste heat of gas transport industry to electricity. Technology provides full electricity autonomy of gas compressor stations, gas distribution stations and points of shields, reducing the specific value of emission of harmful substances.

Secondary heat sources overview

The main sources of medium and low-potential waste heat are industrial production with unused thermal potential in the future irrevocably discharged into the environment with outgoing exhaust gases or coolant. This leads to thermal environmental pollution and to reduce the competitiveness of finished products associated with the energy lost in view of the cost of these products. Current productions of this kind are:

ferrous metallurgy;

the chemical industry;

manufacture of glass;

ceramics production;

manufacture of cement;

high power diesel generators;

gas transportation industry (gas turbine engines).

Since the 2000s, the world began active implementation in the above industries utilizing steam power plants operating on organic Rankine cycle (ORC). ORC utilization units provide conversion of waste heat with 8 to 18 % absolute electrical efficiency without any extra fuel consumption, decreasing the specific value of the emission of harmful substances.

The principle of organic Rankine cycle

ORC is a classical steam closed cycle and consists of (fig. 1): *waste heat vaporizer (4-1)*, where the heat of exhaust gas transfers to a liquid organic working fluid transforming it into superheated steam; *steam turbine* (*1-2*), which converts the potential energy of the working fluid into rotational energy of the rotor; *condenser* (*2-3*), where the organic steam cools, passes into the liquid phase; *feed pump* (*3-4*), which increases the fluid pressure to the required value before the steam turbine.

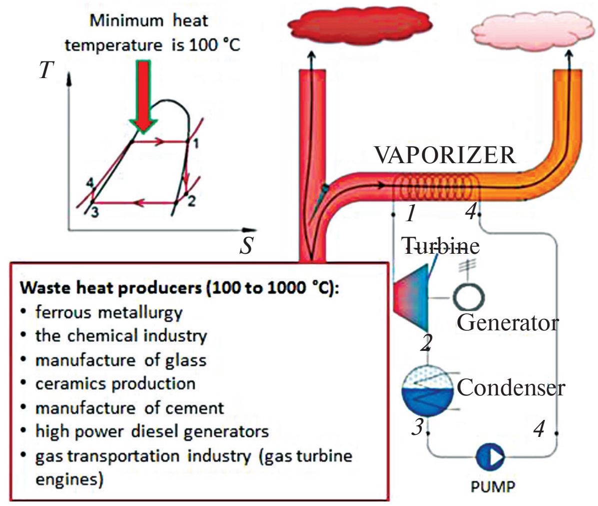


Fig. 1. Structural schema and $T(S)$ diagram of ORC utilization unit [1]

Historical distribution of ORC units have been started at 1890s, when the company "Gas Engine & Power Company" (USA) has sold 500 units (Fig. 2), based on steam piston engine with a working fluid naphtha (flammable hydrocarbon liquid), patented by Franck W. Ofeldt [2].

Next development of ORC was based on researches of new low-boiling organic fluid and have been used in the fields of solar energy (the first solar installation working by ORC with etheric 2,6 kW capacity, was designed by Frank Schumann in 1907 [3]), geothermal power units (the world's first geothermal power unit Paratunskaya with ORC net power of 500 kW, was built in the USSR in 1967 (Kamchatka) [4]), waste heat recovery units and special purpose machinery (autonomous space energy units of 1,5 and 6 kW electricity power of USSR [5]).

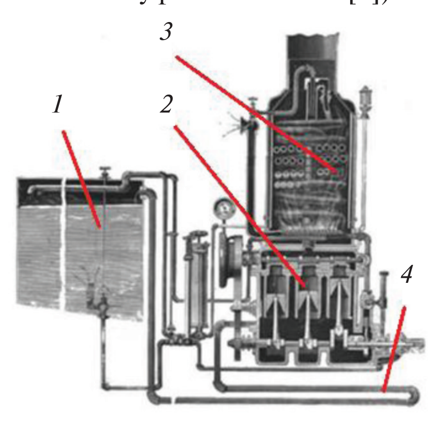


Fig. 2. ORC unit patented by Franck W. Ofeldt in 1897 [2]: *1* – fuel tank; *2* – vaporizer; *3* – steam piston engine; *4* – condenser

Statistics of ORC usage in Europe

Research of the University of Liege (Belgium) in 2009 showed [6] that the main fields of ORC application are next: the utilization of biomass (wood processing and recycling plants, biogas producers) 48 %; geothermal electro stations 31 %; industrial waste heat utilization 20 %; solar systems 1 %.

There are leading manufacturers of commercial ORC units in table 1 [7]. General difference between units is usage of different organic working fluids which have individual chemical and thermodynamic properties what influence deeply at unit's construction. The most dangerous point of some organic working fluid is toxicity what requires a careful unit's seals design.

ORC usage at natural gas transmission infrastructure of Russia

PAO "Gazprom" - the world's largest gas company, owner of the most extensive gas transmission system (more than 160 000 km), the operator about 3800 gas turbine engines (GTE) with total power of 44,3 GW [9].

Further in an article will be considered ORC usage for exhaust gas waste heat recovery of turbine driven gas compressor stations (GCS), characterized by high temperature (350 to 550 °C, depends on GTE efficiency) and large mass flow. This ORC utilization units allow to provide electro autonomy of turbine driven GCS without fuel consumption and to reduce a relative emission of production pollution by 25 % (at maximum recovery of waste heat).

Electricity consumption research of Ltd "Gazprom transgas St.Petersburg" shows that electricity consumption of one GCS is from 200 to 500 kW. In case of necessity of air cooling fans working, the electricity consumption increasing for 500 to 1500 kW, depending on natural gas mass flow and pressure in gas pipeline, environment and earth temperature. This research shows the necessary power of ORC utilization unit, which was selected as 560 kW.

According to European research of 2013 [9], overall exhaust gas waste heat recovery potential of PAO «Gazprom» GCS using ORC utilization units is 3,9 GW at single unit power from 1,2 to 15 MW. The calculation took into account next nuances: reserve GTE power is not taken into account (one reserve GTE for two working GTE, $k_1 = 0,65$); efficiency of ORC unit is around 30 % of GTE efficiency and equals to 10 % ($k_2 = 0,3$), total annual operating time of GTE is around 4000 hours ($k_3 = 0,45$).

Positive exploitation experience of ORC utilization units is presented in the report of the American Association of natural gas for 2009 [10]. Report says that at GCS of North America (USA and Canada) since 1999 have been operated 15 ORC utilization units with total power of 75,5 MW (fig. 3 [11]). All units are made by ORMAT company (USA) and have a power range from 4 to 6 MW. An important fact is that the weight and size characteristics of the organic turbine is several times less than the heat transfer equipment (heat recovery boiler, economizer, evaporator, condenser).

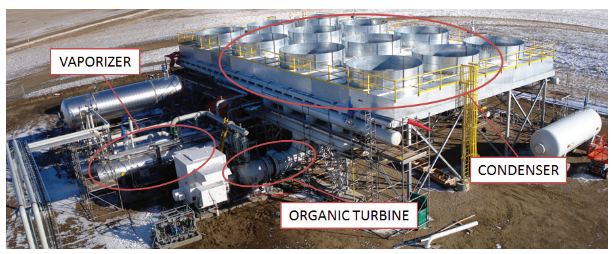


Fig. 3. ORC utilization unit 6MW power working at gas compressor station in Loreburn (Canada) [11]

Table 1

Leading manufacturers of commercial ORC units [7]

Producer	Unit power, kW	Working fluid	Fluid parameters at turbine inlet		Number of working units, pc.
			T, °C	P, MPa	
General Electric Energy (USA)	125	R245fa	121	1,72	>100
Ormat (USA)	400-15000	*n*-Pentane	105-180	–	>200
Turboden (Italy)	200-15000	*n/a*	100-200	–	>260

Emission of production pollution of Russian’s gas transmission network

PAO “Gazprom” gas transmission network is accompanied by large volumes of emission of harmful substances contained in the exhaust gas of GTU. Evaluation of the annual volume of pollutants is shown at figure 4 [12]. Integration of ORC utilization units to PAO “Gazprom” gas transmission network will provide the reducing of a relative emission of production pollution by 25 %. Reducing specific emissions is achieved by converting the heat capacity of exhaust gases in the exhaust gas turbine engine into electrical energy, without additional combustion of fuel.

Electricity production (3,9 GW) without necessity of fuel consumption allows to estimate saving of natural fuel resources. The estimation is done by two ways: classical electricity production using GTU (efficiency 35 %) and combined cycle with GTU and steam turbine (efficiency 45 %). The savings are 11,990 and 9330 thousand ton of conventional fuel per year respectively.

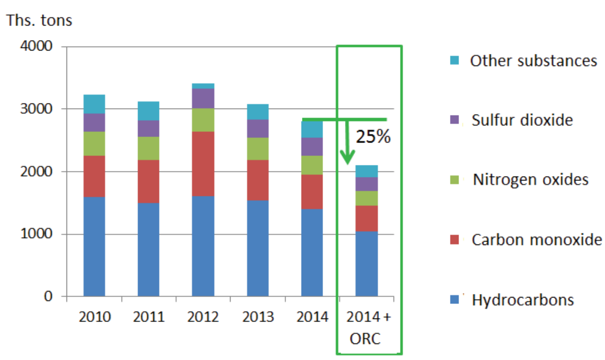


Fig. 4. Annual volume of pollutants of PAO “Gazprom” gas transmission network and potential of its decreasing using ORC utilization units [12]

Experimental stand for organic turbine research

Today at the Russian market of ORC utilization units presented only Turboden company, which has installed at oil refining factory of Lukoil-Perm company the ORC utilization unit (1,8 MW power) running on the heat from the burning of associated petroleum gas. The need for such units is increasing from year to year.

In 2012 the department of «Turbines, hydromachines and aircraft engines» of Peter the Great Saint-Petersburg Polytechnic University has started the development of environmentally friendly ORC utilization unit electrical power of 560 kW (fig. 5) [13], with a non-toxic and ozone-safe working fluid, hexamethyldisiloxane. The unit is able to utilize the industrial waste heat with minimum temperature of 200 °C.

At the present time performed cycle variant calculations, organic turbine design, designed and built an experimental stand for organic turbine model research using air like a working fluid.

The model geometry is equal to designed organic turbine. It means that similarity factor equals to one (fig. 2).

At experimental stand will be researched two turbine types:

high enthalpy drop turbine stage of Peter the Great Saint-Petersburg Polytechnic University construction, which is designed for two-loop organic turbine with working fluid hexamethyldisiloxane;

organic turbine with axialsummetry nozzles.

a)

b)

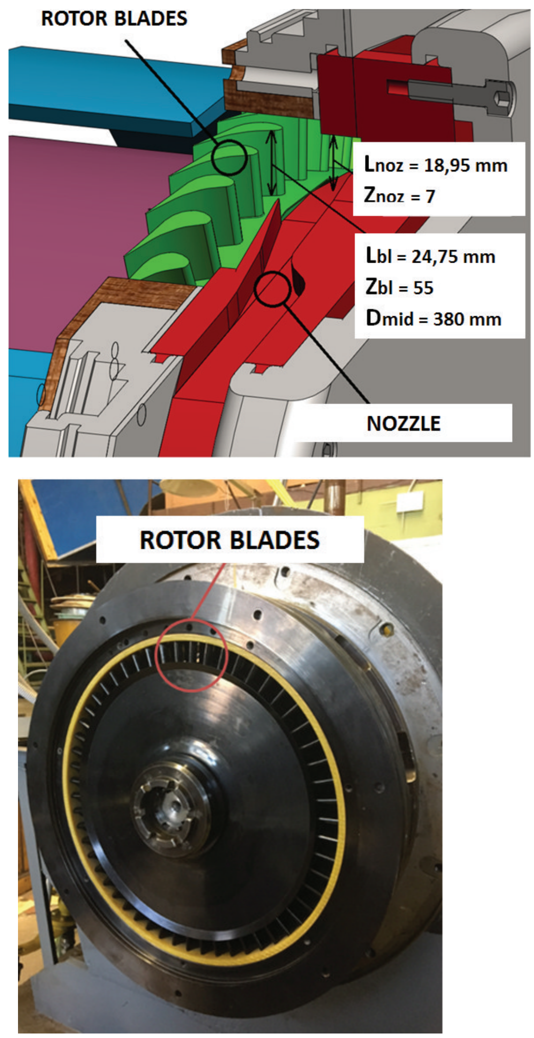


Fig. 5. Construction (*a*) and experimental stand (*b*) of organic turbine air model [13]: L – height; Z – quantity; D – diameter

Problems of organic turbine design and further experimental research at air experimental stand

The complexity of the organic turbine design is linked to a strong change of the working fluid's thermal parameters during flow expansion in turbine's channel. This feature requires the development of nonclassical complex approach to the turbine design comprising a numerical calculation and experimental physical research.

Experimental research of classical models of steam (water vapor) and gas turbines are carried out at experimental air stands using the theory of similarity, and dimensionless turbine criterions. Theory of similarity such turbines involves providing of geometric, kinematic and dynamic similarity.

For correct turbine similarity under condition of turbine geometry preservation, enough to withstand next parameters:

characteristic turbine number U/C_0, where U – rotor blade velocity; C_0 – isentropic spouting velocity;

Mach criterion behind the nozzles M_{C1} and rotor blades M_{W2}, M_{C2} calculated from the relationship $k_m M_m = k_n M_n$, where $k = C_p/C_v$ – specific heat ratio; M – mach number; C_1 – absolute velocity at nozzle outlet; C_2 and W_2 – absolute and relative velocities at rotor blades outlet; "m" and "n" – model and natural turbine stages.

In case of using organic working fluids, the value of the parameter k is strongly dependent on pressure and temperature, making it difficult to direct use the classical theory of modeling for the study of expansion process of hexamethyldisiloxane using air as the working fluid.

The most simple, from a physical point of view, method of organic turbine experimental research is creating an experimental stand with natural (organic) working fluid. However, this method approach leads to a whole range of difficult obstacles.

The complexity of creating a full-scale experimental stand with organic working fluid is that the various working fluids (with different thermal characteristics) may have very different mass flow through the stand, what will require the development, manufacture and application of massive sectional constructions of the steam generator, condenser and different housing parts for placement nozzle diaphragms and impellers. The second complexity is high pressure inside the stand, which may run higher than 1 MPa. It means that the rules need to perform the safe operation of the device and vessels operating under pressure. Finally, some of the used ORC working fluids are toxic or dangerous that requires increased attention to sealing and security systems. Aforesaid says that the experimental stand for organic turbines research cannot be made universal and manufacture with operation of it are expensive.

The way out is to develop new approaches in the framework of similarity theory, allowing to simulate workflows in organic turbines, using experimental air stands. A special feature of this approach is the difficulty or impossibility of the simultaneous holding of similarity criteria of natural and air model turbine stages.

In case of air modeling of designed 560 kW organic (hexamethyldisiloxane) turbine (fig. 5), possible to withstand similarity criterions U/C_0 and M_{C1}, but it is impossible to simultaneously withstand criterion M_{C2} (table 2). It can be explained by high difference between specific heat ratio (k) and gas constant (R) values of hexamethyldisiloxane and air, what leads to significant difference of sound velocity, enthalpy drop and incompatibility of velocity triangles (table 3 and fig. 6).

This particularly applies to the rotor blades outlet triangle velocities – is not achieved axial outlet flow in the model stage, what greatly reduces the efficiency of the model turbine stage.

Table 2

Parameters of natural (hexamethyldisiloxane) and air model turbine stages

Parameter	Dimension	Natural parameters	Model parameters
Mach criterion for nozzle outlet absolute velocity, M_{C1}	–	1,640	1,467
Total inlet pressure, P_0^*	MPa	1,0	0,469
Total inlet temperature, T_0^*	K	477,1	353,16

Ending table 2

Parameter	Dimension	Natural parameters	Model parameters
Static outlet pressure, P_2	MPa	0,04	0,11
Total outlet temperature, T_2^*	K	380,6	291,0
Mach criterion for rotor blades outlet absolute velocity, M_{C2}	–	0,814	0,624
Working fluid	–	Hexamethyl-disiloxane, $C_6H_{18}OSi_2$	Air
Mass flow, G	kg/s	6,513	1,615
Characteristic turbine number, U/C_0	–	0,654	0,645
Rotor blade velocity, U	m/s	238,8	316,4
Absolute velocity at rotor blade outlet, C_2	m/s	111,6	211,5
Rotational speed, n	rpm	12000	15900
Turbine power, N	kW	285,0	97,7
Degree of reaction	–	0,541	0,123

Table 3

Physical parameters of hexamethyldisiloxane and air

Parameter	Dimention	Air	Hexamethyl-disiloxane
R – gas constant	kJ/(kg · K)	287	51,3
$k = C_p/C_v$ – specific heat ratio	–	1,4	1...1,3 = $f(P; T)$
C_p – heat capacity at 100 ^{0}C and 0,5 MPa	J/(kg · K)	1015	2099
a – sound speed at 100 ^{0}C and 0,5 MPa	m/s	387,8	549,5

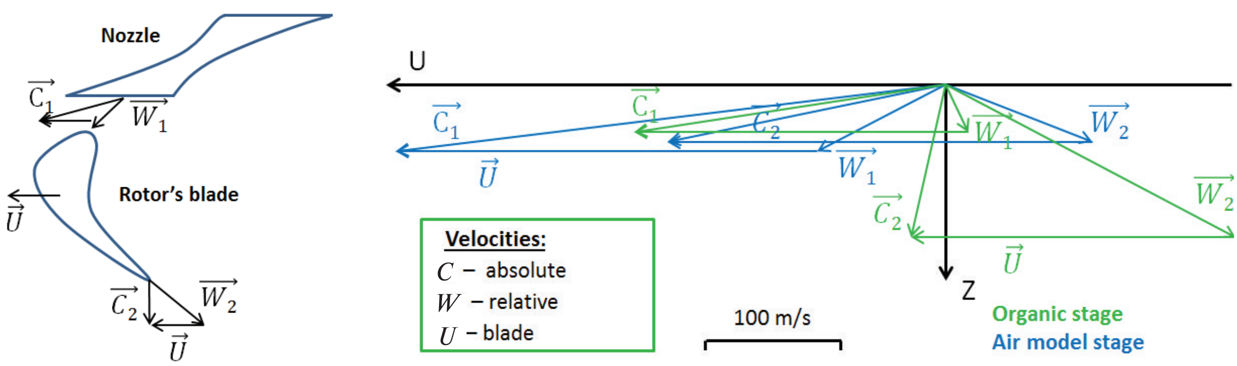


Fig. 6. Velocity triangles of natural (green) and model (blue) turbine stages

A physical modeling to ensure full accordance all the criteria of similarity is impossible. Therefore, as already mentioned, formulated a new approach to modeling of organic working fluids expansion process at experimental air stand.

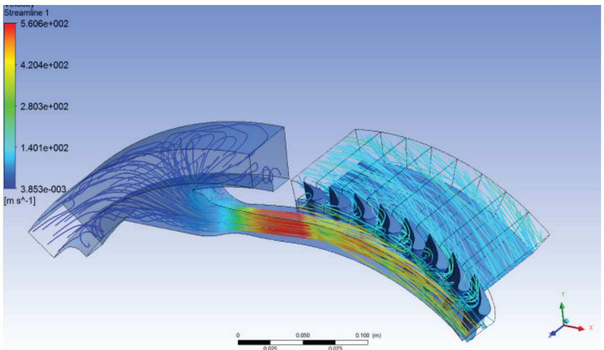
The approach is based on complex research of the expansion process in the turbine by methods of numerical experiment, and methods of physical experiment.

Such a study is currently in progress at the laboratory of the department of «Turbines, hydromachines and aircraft engines» of Peter the Great Saint-Petersburg Polytechnic University and consists of three phases.

The first phase involves the analysis of flow characteristics of working fluid (air) through air model of designed organic turbine. Performing the model in scale 1:1 allows to exclude from the flow analysis the effect of the size factor. This phases includes numerical research (flow's parameters calculation has been completed) (fig. 7) and physical research on the exact geometric model of turbine stage (fig. 5). The design of experimental stand and methodology of physical research are detailed in [13].

Analysis of the results of the first phase will assess, for a given geometry of the turbine stage, the deviation of the numerical research, compared with the physical research. Achieved deviation will be used at the second phase of study.

a)



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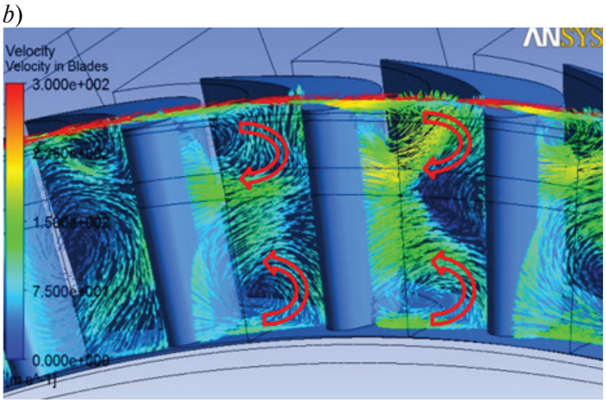

Fig. 7. Results of numerical research of air model of organic turbine stage: *a*) Streamlines through the turbine stage; *b*) The formation of horseshoe vortices in channels between the rotor blades

The second phase consists of carrying out a numerical experiment of organic (hexamethyldisiloxane) working fluid on the same computational mesh (from first phase), based on achieved deviation at the first phase. Computational mesh, as well as the stage geometry, is unchanged.

The third phase consists of comparing and analyzing the results of natural (organic working fluid) and model (air working fluid) turbine researches and confirm the new approach to the theory of computational and experimental modeling of organic working fluids using air as the working fluid.

The final research will be conducted using ORC utilization unit with designed organic turbine. The ORC unit will be installed at GCS "Severnaya" of Ltd "Gazprom transgas St.Petersburg". At the present the ORC unit is under manufacturing and installation (filling of foundation). The launch is scheduled for autumn 2017.

Hexamethyldisiloxane wet steam modeling aspects

A feature of thermo-physical properties of hexamethyldisiloxane is that during the flow expansion in turbine channels from the saturation line to the condenser the diagram wet should be absolutely dry.

However, even if hexamethyldisiloxane enters to the first turbine stage at zero diagram wet, possible the falling out of condensed moisture at the beginning of expansion what may be the reason of gap and drop erosion first of all of nozzles and rotor blades. The process of evaporation of drops is very inertial, requires a lot of time and may not be able to complete until turbine outlet.

Questions of hexamethyldisiloxane moisture-formation, wet phase transformation and it's evaporating during expansion in turbine stage have not been studied and are not reflected in world literature.

To solve the problem of the possibility of a two-phase hexamethyldisiloxane flow simulation assumes the using of air experimental turbine stand with artificial flow moisture by injection the liquid phase.

To complete transfer model test results on natural conditions, except of geometric similarity, it is necessary to provide a range of coincidence of the dimensionless parameters, the number of which is so large that their simultaneous and strict coincidence is impossible in most cases. At the same time empirically established that many of the criteria of similarity within a certain range of their changes have only a minor influence on the final result [14].

Most significant in modeling of two-phase flow are gas-dynamic similarity criteria. As already mentioned, to achieve a full coincidence of similarity criteria is impossible. Therefore, we can only talk about a partial simulation, based on experience and theoretical analysis of the processes chosen system of similarity criteria, the most detailed process describing the study of movement and evaporation of the droplets.

As is known from [14—17], with the partial simulation of the interaction processes of liquid particles with vapor streams and part surfaces, the following points are gas-dynamic similarity criteria: Reynolds Re, Froude Fr, Weber We, Euler Eu, Stokes St, Mach M, Strouhal Sh, the mass and expenditure level of humidity. These parameters are presented for natural (hexamethyldisiloxane) and air model of designed organic turbine stage in table 4.

Table 4

Similarity criteria of natural (hexamethyldisiloxane) and air model of designed turbine stage

Dimensionless flow criterion		Hexamethyl-disiloxane	Air (with water injection)
Reynolds	Re_{C1} Re_{C2}	4,3E+0,6 5,9E+06	5,1E+05 7,4E+05
Strouhal	$Sh = U/C_0$	0,654	0,654
Euler	Eu_{nozzle} Eu_{blades}	1,142 7,963	1,169 0,374
Froude	Fr_{nozzle} Fr_{blades}	4,18E+05 3,67E+04	1,37E+06 1,32E+05
Mach	M_{C1} M_{C2}	1,640 0,814	1,467 0,624
Average diameter of the droplet, m *We* critical = 14	$d1_{nozzle}$ $d2_{blades}$	0,0015 0,0186	0,0301 0,0699

There is a satisfactory agreement between the main criteria: Reynolds, Mach, Strouhal and Euler at nozzle outlet.

Results analysis allows concluding that it is possible to simulate the wet-steam flow of hexamethyldisiloxane at air experimental stand. The requirement of the simulation is providing a necessary droplet size, which depends on critical Weber criterion. Unfortunately unable to find data on the critical value of the Weber criterion for hexamethyldisiloxane, for calculations as a first approximation is set to 14, that is typical for water and steam.

Conclusion

1. The gas transportation network in Russia produces huge amounts of air pollutants, the specific amount of which can be reduced by 25% by using ORC utilization units. The specific pollution decrease achieves by waste heat converting to electricity without burning additional fuel.

2. ORC utilization units allow to provide the electricity autonomous of gas compressor stations, gas distribution stations and points of shields and other objects of Russian gas transport system without additional fuel costs.

3. New approach of ORC design is under creation. It includes methodology of organic turbine research at experimental air stands, what will significantly reduce the time and cost of the development in comparison with the full-scale research at experimental organic stand.

4. It is shown that is possible to model the flow of wet hexamethyldisiloxane vapor, providing a necessary droplet size.

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