Aerodynamics of the Flow Paths of the Vacuum Unit of a Special Cleaning Vehicle in Mining Areas

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The aerodynamic processes occurring in the flow paths of the vacuum device in a special hybrid vehicle intended for mine rail cleaning and the preliminary evaluation of air parameters in the flow paths of the vacuum device are studied. Mathematical modelling of aerodynamic processes was carried out to confirm its performance of rail and air cleaning. The spatial problem of aerohydrodynamics for a single-phase medium by means of a fixed computational grid is solved. Modern computer packages are used for numerical simulation. As a result of the numerical calculations, the pressure losses and maximum flow rate values in the flow paths were determined when the airflow rate varied from 0.5 m^3 / s to 0.27 m^3 / s. The distribution fields of the velocity and pressure module in the intake duct, tank, filter element and silencer are given. It has been shown that at different capacities of the system, the pressure drop in the suction channel ranges from 185 Pa to 300 Pa, the total pressure path loss is 2000 Pa. A mathematical simulation of the filtration and exhaust air damping processes in the filter unit and a vacuum unit muffler was performed. It is shown that the flow rate is reduced to 80%. Analysis of the resulting flow diagrams and aerohydrodynamic parameters confirming the performance of the vacuum unit, which manages flawlessly the mine cleaning.

Keywords: *Special universal vehicle, mine cleaning, attachments, vacuum installation, aerohydrodynamics, mathematical modelling.*

Introduction

Human life activity is mostly the reason for environment pollution. Main places of waste accumulation are public amenities. Such places are public transport route stops and inter-rail space as well as water drainage and sanitary manholes that are often littered with fine wastes (cigarette butts, candy wrappers, paper, small packages and fallen leaves in a mid-season) (Ivanov, 1999), (Murray-Smith, 2019) as well as industrial infrastructure objects, for example, operation (Bołoz & Castañeda, 2018) and sealed off coal mines (Qazizada, 2018).

First railway and train line cleaning devices were designed within the period starting from the end of the 19th century (Herrera, 1880) - to the beginning of the 20th century (Pringle, 1906) and they were self-propelled railway cars with almost no functions and poor manoeuvring performance. These devices were significantly updated during the 20th century and by 70-80s became big vehicles with performance and design similar to the diesel locomotives (Lasser, 1973) and trams (Perrin, 1989) depending on the time period. The last decade of the 20th century and the first decades of the 21st century showed great interest in ecological matters that lead to new special vehicles design promotion. Such devices have very focused specialization due to the strict standards for railway ballast removal procedure.

Today there are not enough universal and environment-friendly samples of special vehicles for railway and tram lines inter-rail space cleaning on the market. A special type of similar devices is designed for railway track ballast removing (Valditerra, 2013) but such devices not just have big size but also are equipped only with railway undercarriage.

The second major group of special railway track cleaning vehicles are railway undercarriage vehicles (Jiyannpieeru, 1996). This group is characterized by considerable size (Theurer and Oellerer, 1991). Such special vehicles are focused ones and are almost impossible to be applied outside the railway track conditions, especially when talking about the urban infrastructure.

Another group of tram line inter-rail space cleaning vehicles that is a wheel mounted and diesel motor driven can be pointed out, for example, Raymond, 1980. Such devices have a smaller size and more functions, but they have a limited size of the collected waste (very small pieces less than 50 grams) and are harmful to the environment due to the diesel engine emission.

Thus, we can point out that the main disadvantages of the existing devices are big size, low functionality and insufficient ecological compatibility of the engines. Consequently, it can be said that the market shows a limited

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range of vehicle designs for rail tracks, yard space and public roads cleaning that combine wheel and rail undercarriage for moving by regular roads as well as by railway tracks.

Analysis of main disadvantages of current devices allowed to develop the list of requirements for special vehicles designed for inter rail cleaning. Such requirements include small size, levity and versatility.

Special vehicles shall be equipped with a waste collection device (Attachment, 2010; Kolotov and Benderskiy, 2019; GOST 27478-87, 1987). Newly designed or upgraded installations require waste grip of maximum volume (GOST 27415-87, 1987; GOST 27478-87, 1987). The analysis of the current designs (Kolotov, 2019) discovered a number of major deficiencies of vacuum-cleaning vehicles thus in order to clean the inter-rail space of the tram lines and streets a special hybrid vehicle for tram line and streets cleaning was designed (Fig. 1).

Fig. 1. Hybrid special vehicle with attachable equipment set.

Main characteristics of special vehicle

The proposed vehicle is equipped with a hybrid drive and motor-wheels. The power for electromotor is supplied from the acid accumulator batteries unit that is charged by diesel-generator, mounted on the vehicle frame or by current collector through step-down transformer while the vehicle moves along the tramline. The combined power of four motor-wheels induces motive force of 5000 N (Sleptsov et al., 2006) enough for special vehicle movement across the country with various landform and angle up to 30° (Kolotov and Benderskiy, 2019). The vehicle is mounted on a chassis with a double undercarriage that allows moving both by roads and by rails however road wheels are driven ones. In order to reduce the weight of the vehicle, its double undercarriage is performed as a frame structure made of composite materials. The quick-turn railway carriage is mounted on a frame, and it gives the direction of the vehicle movement along the rails. Thus the designed vehicle has small size, low weight due to the composite frame materials and mobile as it can move along the rails as well as the road track.

Such a special vehicle (Attachment, 2010) design and dimensions provide the ability to turn within a 20m radius without leaving the rails.

The special vehicle configuration (Fig. 2) includes a waste-collecting tank with special structure (Kolotov and Benderskiy, 2019), vacuum-heating unit and portable attachments of various applications in addition to the above the given vehicle is environmentally friendly and multifunctional.

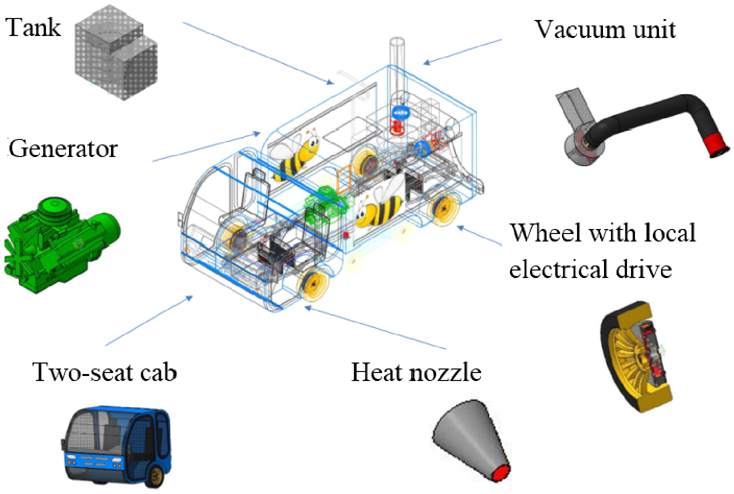


Fig. 2. Special vehicle scheme

A dry weight of the vehicle is 800 kilograms. The weight is uniformly distributed by axles. Each vehicle axle can receive additional load up to 200 kilograms. Removable attachable equipment quickly transforms special vehicle from vacuum cleaning vehicle to filter-exhauster for coal mines cleaning, snow blower, sweeping device, washing or sprinkling machine using the multifunctional drive common for the corresponding unit such as snowblower screw, cleaner brushes, water pump unit of washing or sprinkling machine. The fan included in the vacuum unit generates airflow. Such modifications provide the air supply from the outside and then it is transferred to the operating mechanisms.

The attached equipment of the special vehicle also includes a washing unit that consists of 100 litres tank designed as small volume accumulator used in situations when there is no fire hydrant or water pits. The second main unit is low pressure pumping unit with a capacity of 10 l/min. The drive of attached equipment is a pneumatic one. The main application area of the special vehicle is a tram or railway tracks with stops, yard or near road areas (sidewalks), park areas and cross-country terrain, surfaces with asphalt concrete pavement (parking lots, squares).

The special vehicle module-type construction allows performing various operations. Attachable side trimmers allow for cutting lawns and near-rail territories. Air heated to a certain temperature blown through nozzles maintains the railway switches safe performance during the winter period.

Moreover, the special vehicle can be applied for maintenance/cleaning of the railway tracks in closed coal mines and air filtration in mines. In order to clean the railway track from coal dust, the vacuum unit can be upgraded using the Rainbow exhauster operation principle. The special vehicle attached equipment set is added with a water filter that collects the most part of fine dust. Thus, a designed special vehicle with module accessories has wide effective implication in urban areas as well as specific objects.

One of the main fictions of the device is cleaning of the surrounding space from the garbage. The vacuum-heated unit sucking the waste ensures the environment safety of waste collecting process.

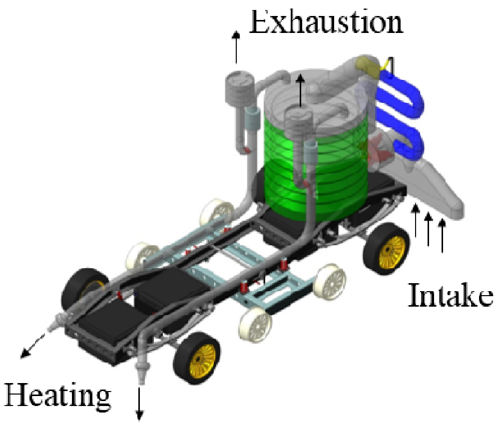


Fig. 3. Vacuum-heating unit of a special vehicle

The vacuum-heated unit of the special vehicle.

Vacuum unit (Fig. 3) design required the calculation of fan power (Kolotov, 2019) that can provide required under pressure that allows sucking waste up to 0.1 kg. Reynolds number estimation (Re> 10^5) indicates the turbulent mode of air circulation.

Figure 4 shows the vacuum unit (Kolotov, 2019) air duct. The radial-flow-fan mounted behind an inlet nozzle sets up required pressure differential that results in low-pressure zone generation upstream the fan and high-pressure zone downstream the fan. The airflow passes through the tank, filter and then out to the atmosphere. The radial-flow-fan with the capacity of Q = 0.5 m^3/s is used as the vacuum unit drive.

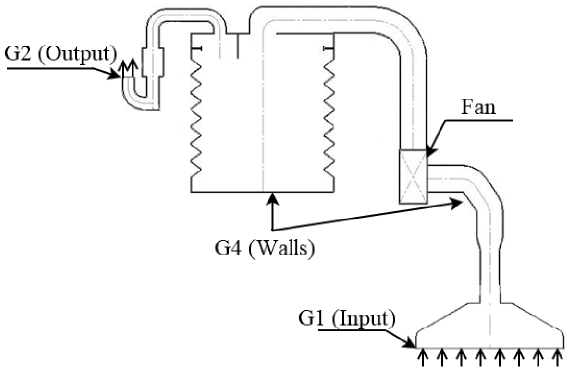


Fig. 4. Vacuum unit air duct

In order to specify the flow structure, gas flow speed rate, hydrodynamic losses the mathematical modelling of aerodynamics processes proceeding in unit flow ducts was performed.

Considering low speeds of air movement in the unit dust (Mach number $M < 0{,}3$) incompressible liquid was chosen as a mathematical model. In this case, the Navier Stokes equation will have the following form:

$$\nabla \boldsymbol{v} = 0 \quad (1)$$

$$\rho \frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t} = \rho \boldsymbol{F} - \nabla p + \nabla(\mu \nabla \boldsymbol{v}) \quad (2)$$

where ρ – gas velocity, p – pressure, v – velocity vector, F – bulk force, μ – dynamic viscosity. Airflow in a unit ducts does not consider fan rotation.

The computational grip is shown in Figure 5. It consists of more than 1 million elements with a maximal dimension of 0.02 mm. Hexahedral elements are used.

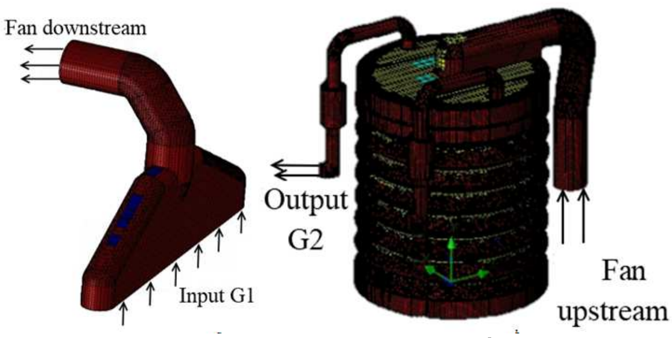


Fig. 5. Computational grip
(a) for decompression zone (b) for over-pressure zone

Boundary conditions are set up in the following way:

for the input zone (G_1 – boundary) gas flow rate and initial turbulence intensity are specified, $G_1 = 0{,}27 \div 0{,}5\, m^3/s \quad Tu_1 = 5\,\%$;

for air bleeding to the atmosphere zone (G_2 boundary) atmosphere pressure is set, $P_{2,3} = 101350$ Pa;

for the walls (G_4 boundary) – no-slip and no-leak conditions;

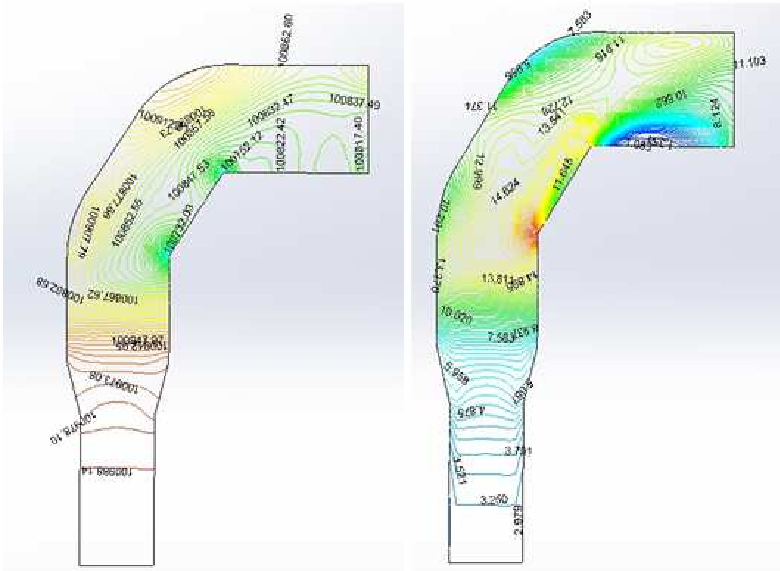
when calculating the flow in a vacuum zone, the physical parameters received in the output section upstream the fan (Fan downstream boundary) become the input parameters (boundary conditions) for the inflow boundary (Fan upstream boundary) for overpressure area downstream the fan;

the airflow passes through the ducts of damper and air filter for better noise damping and environment pollution protection.

Equation system (1)-(2) is averaged by Reynolds number ($R_e > 105$). In order to loop up the obtained system (1)-(2) (Volkov and Emelyanov, 2008) Menter SST (Menter, 1994) turbulence model was applied (empirical factor of dynamic viscosity $c_\mu = 0{,}09$).

The calculations discovered flow structures in unit working ducts, pressure and velocity fields.

Figure 6 shows the flow structure in the unit intake manifold that demonstrates a dead zone with dimensions 0.18x0.048 m.



a b

Fig. 6. Airflow structure in an intake manifold
(a) isobars; (b) isotaches

Figure 7 shows the flow structure in the intake convergent short tube. Fig. 7a shows that differential pressure is 300 Pa, provided that maximum speed does not exceed 20 m/s.

Local separation zone in a transition area of unit intake into the tube has the following dimensions: from 0.03x0.02 m in the intake manifold up to 0.1x0.4m in the tube (Elbakian, 2018; Kalentev et al., 2017).

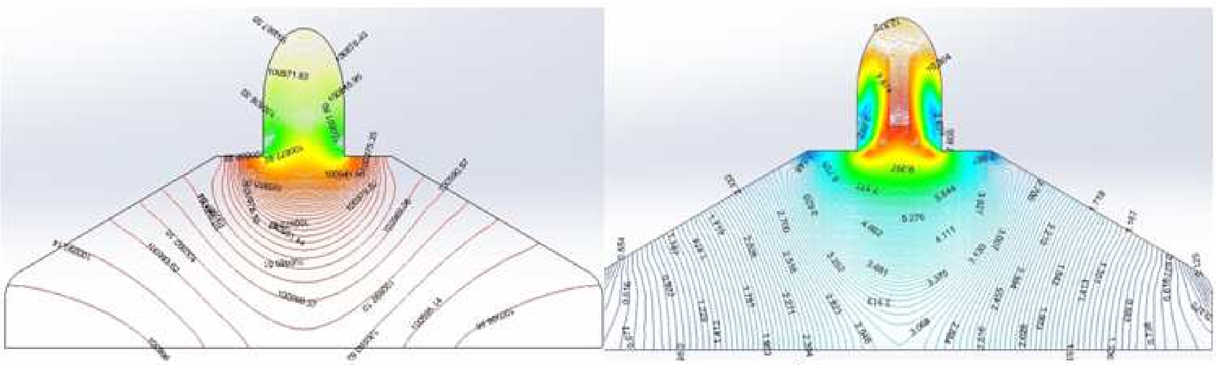


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Fig. 7. Airflow structure in a unit intake
(a) isobars; (b) isotaches

Flow variation form $G_1 = 0{,}5\, m^3/s$ $G_1 = 0{,}27\, m^3/s$ leads to pressure difference reduction up to 185 Pa.

Results prove that decompression in the output area of the duct required for lifting and collection of up to 0.1 kg of waste into the tank is generated.

The flow structure, isobars and isotaches in the collector are shown in Figure 8.

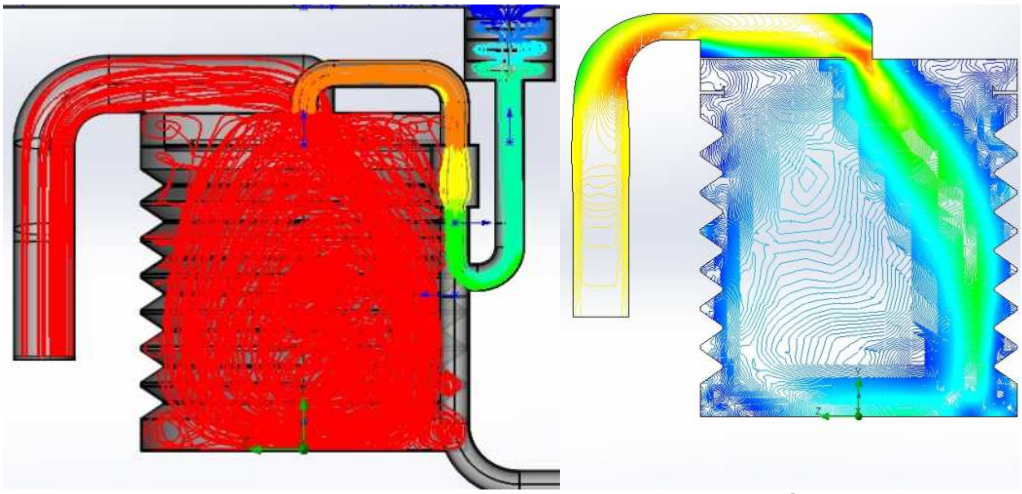

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Fig. 8. Flow structure in the collector
(a) space flow lines (b) isotaches

Fig 8,b shows that the flow going upstream the collector is of stream-like type. Air exhaustion is performed through an outlet on the cover of the collector. Circulation zone (Fig. 8, a) with dimensions of (0.4x05m) is generated in the central area of the collector. Air velocity in the tank is reduced due to interaction with sidewalls and bottom. Airflow turn makes the waste settle down on the tank bottom.

Air from the tank gets into the filter and then to the damper to reduce the noise. Airflow structure in filter and damper ducts is shown in Figure 9.

Exhausted air filtration process demonstrates the flow pressure reduction ($\Delta p = 767 \quad Pa$) and pocketing near the filter walls caused by the sudden widening of the channel.

After the air leaves, the filter flow velocity increases up to 20 m/s. The damper is essentially a cylinder with labyrinth type working space arrangement. Airflow velocity 80% reduction to $v = 1 \div 3 \quad m/s$ has been observed.

Common resistance losses in the channel are equal to 2000 Pa.

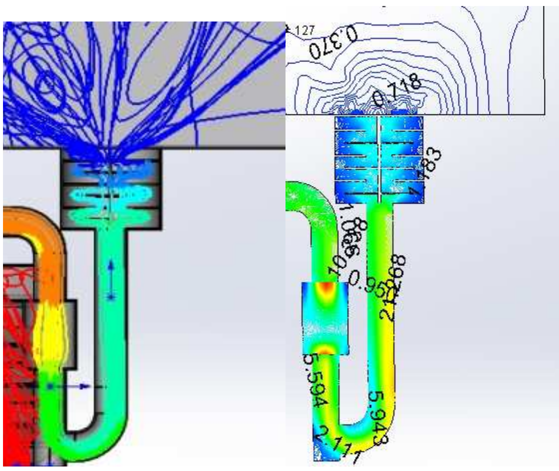

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Fig. 9. Airflow structure in filter and damper ducts:
(a) space flow lines (b) isotaches

The railway switches can be covered with ice during the winter period due to the low temperatures. The special vehicle vacuum- heated unit can redirect the exhaust airflow from the filtering and dumping system into the railway heating system that contains air duct, turbular heating element and nozzle from each feeding side (Fig. 3).

Basing on the theoretical calculation spiral type turbular heating element with a power of 1.8 kWt was selected. In order to check the efficiency of the designed system and approve the turbular heating element power mathematical simulation of aerodynamic and thermophysical processes generated in air ducts, nozzle and near the heated surface, was performed (Bako, 2016). Couples heat transfer stationary problem was solved. Gas escape structure from the nozzle and its interaction process with the rail is shown in Figure 10.

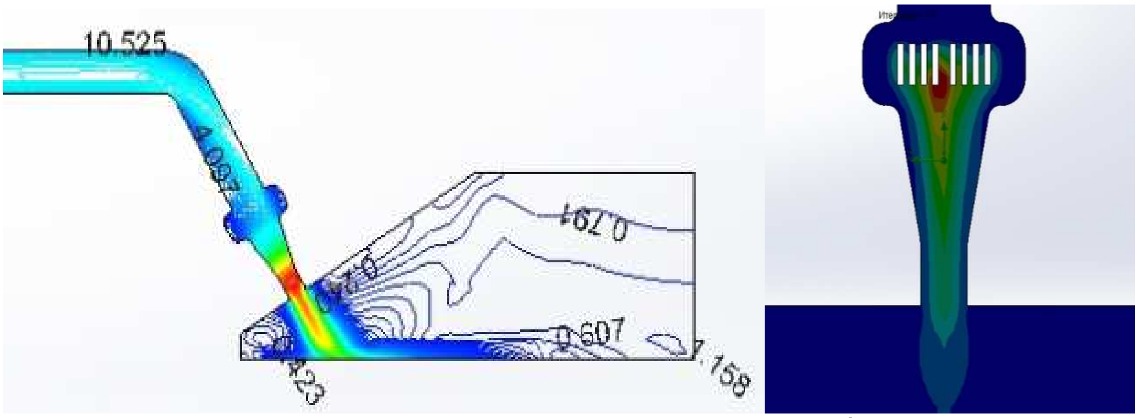

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Fig. 10. Gas escape structure from the nozzle: isotachs (a) and temperature field (b)

Isotach structure analysis is indicative of the heated gas escape from the nozzle of a stream like type. In order to provide exhausted air continuous heating, the turbular heating element construction was corrected considering preliminary calculations. Nozzle area temperature field analysis approves the heating process uniformity and temperature distribution in the flow- rail contact zone (5 ÷ 20 0C) indicates that the supplied heat is enough for railway switch heating (ice melting). Thus, the selected turbular heating element power was proved to be enough for the railway switch heating (Kolotov, 2019).

Results

1. The universal multi-functional special vehicle for inter-rail space waste cleaning was designed.
2. The outstanding feature is an application of the environment-friendly hybrid unit that include electrical motor-wheels and combustion engine. The designed vehicle has double undercarriage that allows moving along roads and railway tracks.
3. The capabilities of the vehicle are increased due to module accessories application. Particularly, beyond the waste cleaning, it is possible to install trimmers for railway lawn cutting, to clean the railway switches during the winter using heated gas streams and some other attachable devices.
4. Mathematical simulation of aerodynamic processes in the vacuum unit was performed. Pressure fields, velocities and flow structure calculation analysis confirms the vacuum unit working efficiency. It was discovered that unit intake fan operation mode ensures pressure difference in the range from 185 Pa up to 300 Pa that allows lifting the waste weighing up to 100 gr. Total resistance losses are smoothed by fan power and do not influence the efficiency of the structure (Cernecky, 2015).
5. Mathematical simulation of exhausted air filtration and damping processes in the filtering unit and vacuum unit damper was performed. It is showed that the flow velocity is reduced to 80%.
6. Numerical computation of the turbular heating element power enough to heat the ice up to 0.2 m height appearing on the railway switches during winter was performed. The selected turbular heating element power of 1.8 kWt and nozzle heating flow uniformity was computationally proved enough It was shown that if the turbular heating element surface temperature is 650^0C the spiral form of the turbular heating element allows to heat the air up to 60^0C in the flow middle, that ensures the nozzle outflow air temperature from 5^0C to 20^0C. Heated air exposure during 5 minutes allows to melt up to 16 kg of ice and totally heat the railway switch.
7. It is shown that if the vacuum unit is upgraded (water cleaning), the vehicle can be used in closed mine installations to clean the space form coal dust and coal coarse fragmenting.

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