Numerical simulation of aerodynamic processes in the fan in the diesel locomotive cooling module

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Abstract. The article is devoted to the numerical assessment of the characteristics of the fan of the cooling module of a diesel locomotive. In the work, the authors consider modern methods and approaches to numerical modeling of fans used in cooling systems of railway diesel locomotives. The focus is on fan performance analysis. The results obtained allow us to better understand and optimize fan operation in the context of diesel locomotive cooling systems, which can help improve the efficiency and reliability of these systems as a whole. The study is important for engineers and specialists in the field of railway transport.

1 Introduction

The introduction of modern engineering solutions in technical systems plays an important role in increasing their efficiency, reliability and cost-effectiveness. In this context, modeling and numerical analysis of processes become an integral part of the development and optimization of various technical systems. Particularly important is the use of simplified engineering models, which can significantly reduce the time and resources spent on calculations, while maintaining sufficient accuracy of the results.

One of the critical aspects in vehicles is an effective cooling system, especially for diesel locomotives, where reliable operation of engines and other heat-generating components is fundamental to safety and operational efficiency. Fans play a key role in cooling systems [1], providing the necessary air flow and controlling heat transfer processes. Depending on the task, the use of simplified engineering models of the fan will significantly reduce the time and resources [2] required for the numerical analysis of diesel locomotive cooling processes, which contributes to faster and more efficient development of new cooling systems and optimization of existing ones. In addition, the results of the study can be used to make important technical decisions and improve the overall performance and reliability of diesel locomotives.

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The purpose of this article is to consider the use of simplified engineering fan models for numerical simulation of processes in the cooling module of a diesel locomotive. The basic principles and approaches to the development of such models, their advantages and limitations will be discussed. Comparison of numerical simulation results with real experimental data will also be considered to evaluate the accuracy and suitability of simplified models.

2 Application of simplified engineering fan models for numerical simulation of processes in the cooling module of a diesel locomotive

3D Fan Zone [3] is used as a simplified engineering model of the cooling module fan. Using the 3D Fan Zone model allows you to replace the "real" fan design with a disk with equivalent characteristics. During the calculation process, the results of the integral characteristics are comparable to the results of direct modeling with moving coordinate systems. At the same time, the cost of machine resources is significantly less and this allows you to speed up the process of calculating many design points. The 3D Fan Zone model does not require calculating the rotation of the mesh; it is possible to set the width of the fan in the direction of the flow, as well as determine the tangential and radial components of the speed.

To validate and evaluate the applicability of the 3D Fan Zone model, a series of calculations were carried out and compared with experimental data. In accordance with the requirements of GOST 10921-2017 [4], calculation models of test benches were prepared, which are shown in Figures 1 and 2. The model for numerical determination of the fan characteristics consists of an input part with an electric motor, a fan or virtual disk, a straightening device and an output area.

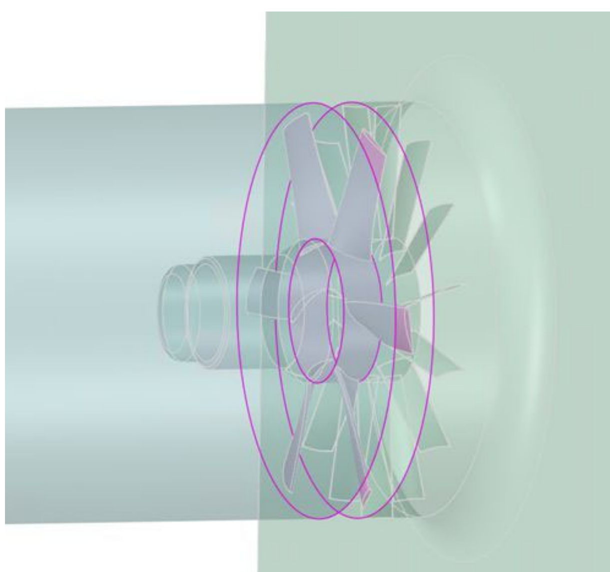


Fig. 1. Calculated geometry of a virtual test bench with real fan geometry.

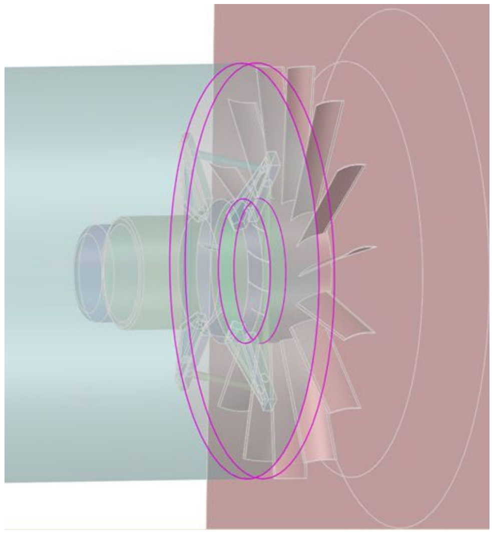


Fig. 2. Calculated geometry of a virtual test bench with a 3DFanZone virtual disk.

Figure 3 shows the overall dimensions of the main elements of the virtual test bench in accordance with GOST. The size of the fan area varies according to the model used. The inlet section is sized according to experimental data.

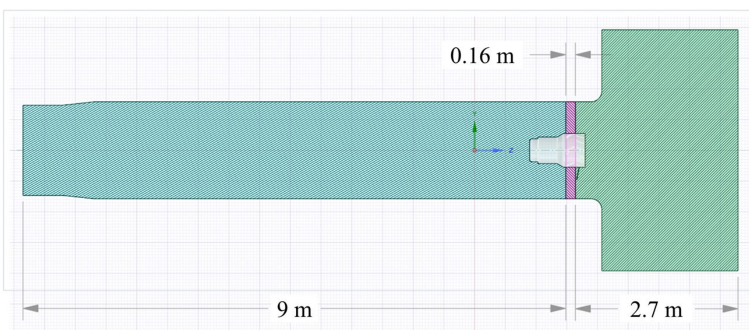
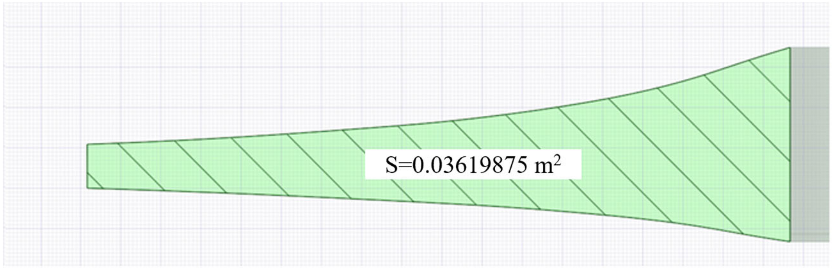
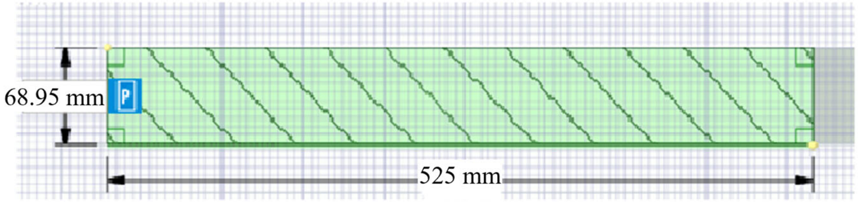


Fig. 3. Virtual test bench dimensions.

3D Fan Zones are a zone of fluid cells that simulate the effect of an axial fan by applying a distributed pulse source to a disk-shaped volume of fluid (that is, the volume covered by the blades). The parameters of the equivalent disk are selected based on the cross-section of the volume swept by the fan blades during its rotation. The cross-sectional area formed by the rotation of the fan blades of a real design is equal to 0.036199 m^2 (Figure 4, a). The outer radius of the fan is 0.805 m, the inner radius is 0.28 m. The cross-sectional shape of the virtual fan disk is a rectangle. Based on the parameters of the cross-section of the fan torus, the height of the disk should be equal to 0.06895 m (Figure 4, b). Table 1 shows the parameters of the 3D Fan Zone virtual disk.



a)



b)

Fig. 4. Cross-sectional area of the swept volume of the fan blades and virtual disk: a) the cross-sectional shape formed by the rotation of the fan blades of the actual design; b) cross-sectional shape formed by the rotation of the virtual fan blades.

Table 1. 3D Fan Zone virtual disk settings.

Parameter	Value
The outer radius of the fan is, m	0.805
The internal radius of the fan is, m	0.28
Disc height, m	0.06895
Speed profile inflection point	0.25

Figure 5 shows the flow-pressure characteristics of the fan. The fan characteristics parameters for 3D Fan Zone were selected from a comparative analysis of numerical and physical experiments. Additionally, points have been added to ensure a smooth description of the characteristic by a second-order polynomial, which will be used to extrapolate data when performing calculations.

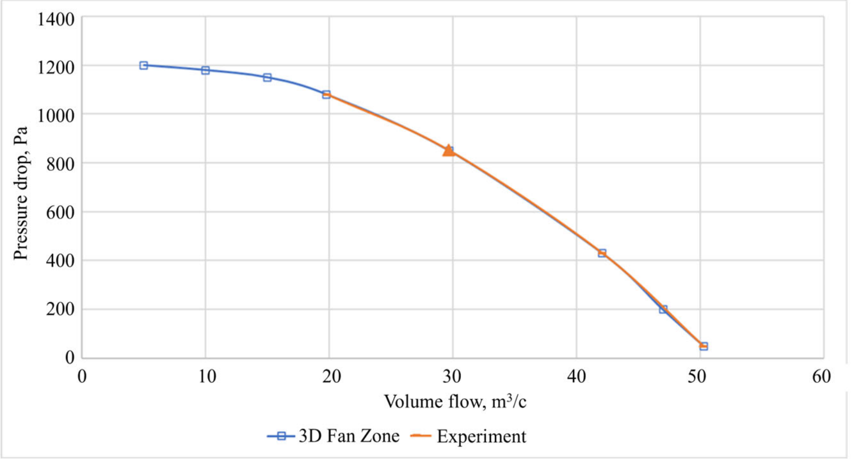
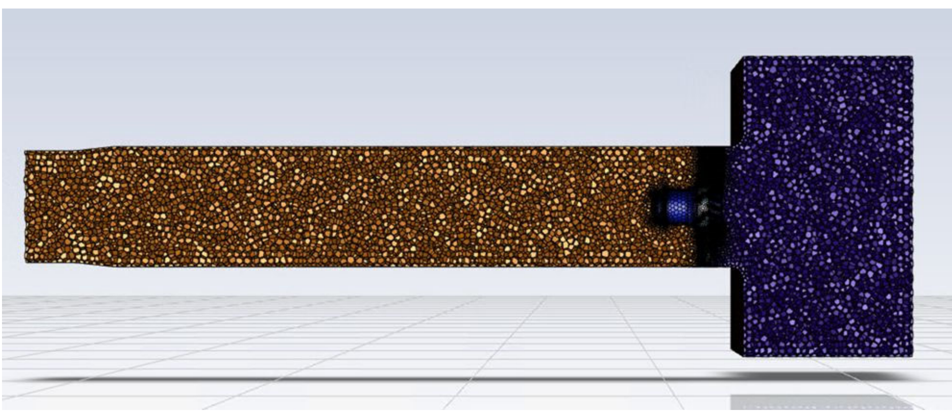


Fig. 5. Flow-pressure characteristics of the 3D Fan Zone fan.

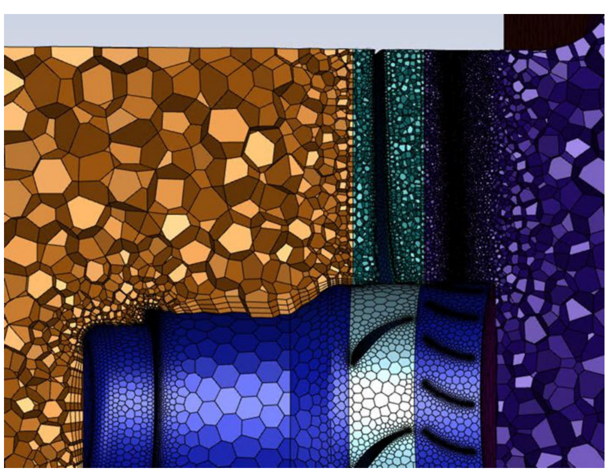
The computational mesh used for this problem is polyhedral. Polyhedral cells allow you to construct a mesh that provides high accuracy of calculations and is economical in terms of computing resources. Also, the use of polyhedral cells allows calculations for highly turbulent flows. To evaluate and more accurately calculate the flow around the straightening vane blades, mesh refinement was specified. The minimum cell size was set to 1 mm, the maximum size was 60 mm, the degree of curvature was 12. The parameters of the prismatic layer were specified as follows: the height of the first layer was 500 μm, the number of layers was 3, and the growth coefficient was 1.2.

A grid model of a virtual stand (Figure 6, a) for testing the real geometry of the fan is shown. A polyhedral element is used as the final volume, because behind the fan the flow is highly swirling. The total grid size was 4,034,261 cells. The minimum quality for orthogonality is 0.28.

Figure 6 shows a grid model of a virtual bench (Figure 6, a) testing a fan in real geometry (Figure 6, b) and using the 3DFanZone virtual disk (Figure 6, c). A polyhedral element is used as the final volume, because behind the fan the flow is highly swirling. The total grid size averaged 1,401,333 cells. The minimum quality for orthogonality is 0.30.



a)



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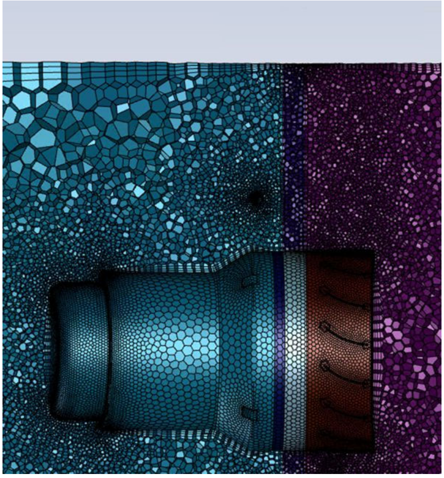

c)

Fig. 6. Grid model of a virtual fan test bench with real geometry: a) virtual stand model; b) virtual testing of the fan in real geometry; c) virtual fan tests using the 3DFanZone virtual disk.

Figure 7 shows the boundary conditions. For modeling, a type of stand with a free exit is used (Figure 7, item 2). At the inlet (Figure 7, item 1) and outlet (Figure 7, item 2) the pressure is set to the calculation domain. The outlet pressure is set to atmospheric pressure of 99,324 Pa. The outlet air temperature is equal to the inlet air temperature, because the cooling module uses ambient air to operate. The output region has been expanded to obtain a more stable solution at the exit section from the straightener. The size of the fan area varies according to the model used. The inlet section is sized according to experimental data.

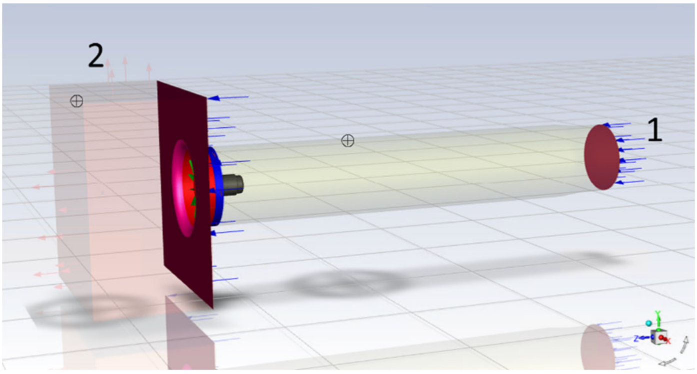

Fig. 7. Boundary conditions: 1 – entrance to the computational domain; 2 - exit from the calculation domain.

For comparison with the results of calculations of the real geometry of the fan and calculations in the 3D Fan Zone setting of the locomotive cooling module, in accordance with the initial data, a data set of experimental results was prepared, which is presented in Table 2.

Table 2. Experimental results dataset.

Dynamic pressure, Pa	362.0	136.0	110.0	51.0	15.0
Total pressure, Pa	406	1108	1176	1351	1469
Static pressure, Pa	44	972	1066	1300	1454

Rotation speed, rpm	1504	1477	1475	1477	1481
Flow speed, m/s	25.2	15.5	13.9	9.5	5.1
Volume flow, m^3/s	43.6	26.7	24.0	16.4	8.9

Table 3 presents the results of numerical simulation of the fan as part of the stand in a model of real geometry. Table 4 presents the results of a comparison of physical and numerical tests of real fan geometry. As you can see, the difference between total and static pressure is on average 32-38%. This difference is due to the insufficient accuracy of the description of the geometric model of the test bench (the existing geometry of the fan wheel blades is not accurate, obtained in the Parasolid format, which in itself determines the loss of accuracy in constructing the curved surfaces of the blades; thus, to carry out such an analysis, the use of high-precision geometry in original construction format).

Table 3. Results of numerical simulation of a fan as part of a stand in a model of real geometry.

Dynamic pressure, Pa	362.0	136.0	110.0	51.0	15.0
Total pressure, Pa	422.3	747.4	782.4	869.8	929.7
Static pressure, Pa	60.3	611.4	672.4	818.8	914.7
Rotation speed, rpm	1504	1477	1475	1477	1481
Flow speed, m/s	25.0	15.1	13.8	9.4	5.1
Volume flow, m^3/s	43.6	26.7	24.0	16.4	8.9

Table 4. Comparison of the results of numerical simulation of a fan as part of a stand in a model of real geometry with experimental data

Dynamic pressure	0.00%	0.00%	0.00%	0.00%	0.00%
Total pressure	4.0%	32.6%	33.5%	35.6%	36.7%
Static pressure	37.0%	37.1%	36.9%	37.0%	37.1%
Rotation speed	0.00%	0.00%	0.00%	0.00%	0.00%
Flow speed	25.0%	15.1%	13.8%	9.4%	5.1%
Volume flow	0.00%	0.00%	0.00%	0.00%	0.00%

Table 5 presents the results of numerical modeling of the fan in the 3D Fan Zone setting. Table 6 presents the results of a comparison of physical and numerical tests of the fan geometry in the 3D Fan Zone setting. As you can see, the difference between total and static pressure averages 0.3-3%. When using the 3D Fan Zone virtual disk, generalized fan parameters and flow-pressure characteristics are used. The flow characteristic is also determined from experimental data. In this approach, the characteristic is specified directly from the interpolated characteristic of the fan, which ensures good convergence. In subsequent calculations, attention should be paid to the output flow velocity vectors, which determines losses after the fan.

Table 5. Results of numerical modeling of a fan as part of a stand in the 3D Fan Zone setting.

Dynamic pressure, Pa	362.0	136.0	110.0	51.0	15.0
Total pressure, Pa	407.3	1083.5	1168.2	1342.8	1429.9
Static pressure, Pa	45.3	947.5	1058.2	1291.8	1414.9
Rotation speed, rpm	1504	1477	1475	1477	1481
Flow speed, m/s	25.2	15.5	13.9	9.5	5.1
Volume flow, m^3/s	43.6	26.7	24.0	16.4	8.9

Table 6. Comparison of the results of numerical modeling of a fan as part of a stand in the 3D Fan Zone setup with experimental data.

Dynamic pressure	0.00%	0.00%	0.00%	0.00%	0.00%
Total pressure	0.3%	2.2%	0.7%	0.6%	2.7%
Static pressure	37.0%	37.1%	36.9%	37.0%	37.1%

Rotation speed	0.00%	0.00%	0.00%	0.00%	0.00%
Flow speed	1.9%	1.9%	1.9%	1.9%	1.9%
Volume flow	0.00%	0.00%	0.00%	0.00%	0.00%

Figure 8 shows graphs comparing physical experiments and numerical simulations of a fan using a model of real fan geometry and a 3DFanZone virtual disk.

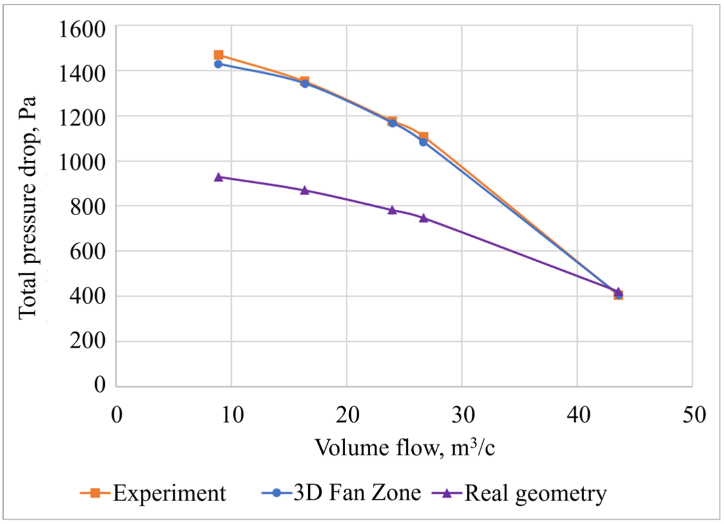

Fig. 8. Graph comparing the results of physical and numerical modeling of a fan as part of a test bench.

3 Conclusion

As a result of a comparative analysis of the numerical aerodynamic calculation of the locomotive cooling module fan in real geometry, the simplified 3D Fan Zone engineering model and experimental data, the following conclusions were obtained.

Numerical calculation using real geometry and a simplified 3D Fan Zone engineering model achieved good accuracy in predicting the characteristics of the aerodynamic process. In this approach, the characteristic is set directly from the interpolated characteristic of the fan, which ensures good convergence. In subsequent calculations, attention should be paid to the output flow velocity vectors, which determines losses after the fan. The accuracy of the results in real geometry turned out to be worse, which is probably due to the use of inaccurate geometry in the Parasolid format, which in itself determines the loss of accuracy in constructing curved surfaces of the blades. Increased accuracy can be achieved by having the exact geometry of the fan wheel blades in the build format. When using the fan flow-pressure characteristic in the 3D Fan Zone engineering model, the results turned out to be closer to the experimental values.

Simplified 3D Fan Zone Engineering Model provides a quick and relatively easy way to perform calculations. It can be useful for preliminary analysis or evaluation of aerodynamic performance in the early stages of design when given (known) fan performance requirements are available. At the same time, using real geometry is more labor-intensive, but provides more accurate results, which is important for the final optimization of the cooling system.

Both numerical approaches demonstrate good agreement with experimental data under certain conditions and calculation purposes: the presence of specified requirements for the characteristics of the fan in order to check the operation of the fan as part of the product for the 3D Fan Zone model and the presence of the exact geometry of the fan blades in order to clarify the characteristics of the fan for calculation real geometry. This determines the choice and applicability of the considered numerical methods, and the correspondence of the results to the actual operating conditions of the fan. Thus, numerical calculations can be used to complement experiments to predict and optimize aerodynamic performance.

In general, a comparative analysis of the numerical aerodynamic calculation of the locomotive cooling module fan in real geometry, the simplified 3D Fan Zone engineering model and experimental data allows us to obtain important engineering data and determine the optimal parameters of the cooling system, helping to improve the efficiency and reliability of the diesel locomotive.

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