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NUMERICAL MODELLING OF SNOW LOADS. VERIFICATION AND VALIDATION FOR THE KEMEROVO MUSEUM, THEATRE AND EDUCATION COMPLEX

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Abstract: This paper presents the results of numerical and physical modelling of snow loads for a unique facility, conducted within the verification procedure of Ansys Fluent in the RAASN system. By analysing the grid and iteration convergence, the applicability of the steady-state (RANS) simulations and three turbulence models (k-ω SST, GEKO-0.70 and GEKO-1.25) is verified for the snow loads determination. The results are compared against experimental data obtained in the MSUCE wind tunnel. A simpler approach to error estimation is utilised since previous research revealed weak applicability of such widely used methods as Richardson extrapolation and approximate error spline. It is shown that the GEKO-0.70 turbulence model (with the separation coefficient C_{SEP} = 0.70) provides a better fit to the wind tunnel data than GEKO-1.25 and k-ω SST. 4. It is confirmed that Ansys Fluent allows the snow loads determination on buildings of complex shape with the accuracy sufficient enough for practical purposes, provided that modern turbulence models and methods set out in the STO "Numerical modelling of wind and snow actions" are used.

Keywords: computational fluid dynamics (CFD), numerical modelling, snow loads, verification, validation

ВЕРИФИКАЦИЯ И ВАЛИДАЦИЯ ЧИСЛЕННОГО МОДЕЛИРОВАНИЯ СНЕГОВЫХ НАГРУЗОК НА ПРИМЕРЕ МУЗЕЙНОГО И ТЕАТРАЛЬНО-ОБРАЗОВАТЕЛЬНОГО КОМПЛЕКСА в г. Кемерово

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Аннотация: Для уникального здания представлены результаты численного и физического моделирования снеговых нагрузок, полученные в рамках процедуры верификации в системе PAACH программного комплекса ANSYS Fluent. С помощью анализа сеточной и итерационной сходимости расчётов проверяется применимость для определения снеговых нагрузок стационарной постановки (RANS) и трёх моделей турбулентности: k-ω SST, GEKO-0.70 и GEKO-1.25. Результаты сопоставляются с экспериментальными данными, полученными в аэродинамической трубе НИУ МГСУ. В связи с тем, что предыдущие исследования выявили слабую применимость таких широко распространённых методов, как экстраполяция Ричардсона и аппроксимация ошибки сплайном, для оценки погрешностей используется упрощённый подход. Выявлено, что модель турбулентности GEKO-0.70 (с параметром C_{SEP} = 0.70) позволяет получить лучшее соответствие данным из аэродинамической трубы, чем GEKO-1.25 и k-ω SST. Установлено, что Ansys Fluent позволяет определять снеговые нагрузки на покрытия сложных форм с достаточной для прикладных задач точностью при условии использования современных моделей турбулентности и методов, прописанных в СТО «Численное моделирование ветровых и снеговых воздействий».

Ключевые слова: вычислительная гидрогазодинамика, численное моделирование, снеговая нагрузка, верификация, валидация

1. INTRODUCTION

Development of reliable and robust methods of snow loads calculation for buildings and structures remains an urgent task in civil engineering due to the growing number of unique facilities that are being designed and constructed in dense urban areas, since building codes cannot provide snow loads for their complex roofs.

Currently, the following methods are used to calculate snow loads:

1. Building codes' provisions and analytical methods (inapplicable to unique facilities);
2. Physical modelling [1, 2];
3. Numerical modelling [3-9];
4. Monitoring and in-situ measurements [10, 11] (mainly academic research);
5. Machine learning and neural networks [12] (academic purposes only to this date).

Physical (experimental) modelling in WTs and water flumes remains the generally accepted method of snow loads calculation. A reliable methodology for such modelling was proposed and developed over the course of the second half of the XX century, which now provides a sufficient level of plausibility under a number of limitations. Still, the high costs of construction and maintenance of WTs, poor scalability, significant simulation time, low information content and other limitations call for development of competing methods which can be applied in practice.

Numerical (mathematical) modelling, especially using CFD methods, appears to be a more prospective direction, being devoid of the WT limitations and promising potentially faster research. Methodologies for numerical modelling of snow loads have been developed independently by many researchers, which are now being gradually legitimised in the regulations of technologically advanced countries, STO [13], ASCE 7-22.

At this time, a synthetic combination of numerical and physical modelling, often labelled "hybrid modelling", allows to gather the most comprehensive information on snow loads for any given roof [13]. Due to high computational and time costs posed by scale-resolving transient approaches (e.g., utilising LES model), steady-state (RANS-based) approaches [4] remain the most used ones in numerical modelling for fast snow loads calculation.

To confirm the reliability of numerical modelling results, a verification and validation (V&V) procedure is required. The most general definitions of V&V are provided in GOST [14] and ASME [15], although they do not regulate specific areas of application, such as structural aerodynamics.

In structural aerodynamics, ***verification*** is reduced to evaluating the errors of the numerical model (iteration, time, grid, etc.) and investigating convergence, since the exact solutions of numerically solved equations are unknown [13, 16-19]. ***Validation*** is more straightforward and complies with [14, 15], however, generally, the results of numerical modelling can only be compared with the results of physical modelling.

In the present paper, the V&V procedure of the numerical modelling of snow loads was carried out for a unique facility of the Kemerovo Museum, Theatre and Education Complex (hereinafter, the *Kemerovo MTEC*). Three turbulence models were considered: k-ω SST, GEKO-0.70 and GEKO-1.25 (with separation parameter C_{SEP} = 0.70, 1.25, respectively). Grid and iteration convergence were investigated. The results of numerical modelling were compared against experimental data obtained in the MSUCE WT.

The work was carried out within the verification procedure of Ansys Fluent for the problems of "determination of wind and snow actions on buildings and structures on the basis of numerical solutions of the equations of aero-hydrodynamics" in the system of the Russian Academy of Architecture and Construction Sciences (RAASN) [20].

2. CASE AND METHODOLOGY

2.1. Case description

In this paper, the Kemerovo MTEC (Fig. 1) was investigated.



Figure 1. Renders of the Kemerovo MTEC

The Kemerovo MTEC has a complex deconstructivist shape, with façades made of glass and metal elements. The building is 10 floors high with a total area of approximately 81100 m^2, and also has an underground parking. The Kemerovo MTEC is planned to house branches of the Mariinsky Theatre and the State Russian Museum, as well as the Kuzbass Arts Centre. The facility's ensemble consists of four parts: a "floating cloud" theatre, two "crystals" (a museum and an art centre with workshops), and a public foyer.

The study investigates snow deposits on the facility's roof obtained through physical and numerical modelling. Numerically, the deposits are calculated using wall shear stress (τ_w):

$$\tau_w = \mu \, \partial u/\partial y \, |_{y=0}, \qquad (1)$$

where μ is the dynamic viscosity of the flow; u is the velocity of the flow along the boundary; and y is the height above the boundary. The values of wall shear stress are converted into numerical snow deposit maps using a methodology described in [3, 4].

The simulations were carried out for two characteristic angles of attack, 0° and 90° (the widthwise and the lengthwise flow directions, respectively, see Fig. 2).

Physical snow deposit maps were obtained in the MSUCE WT through physical modelling at a 1:200 scale (Fig. 3).

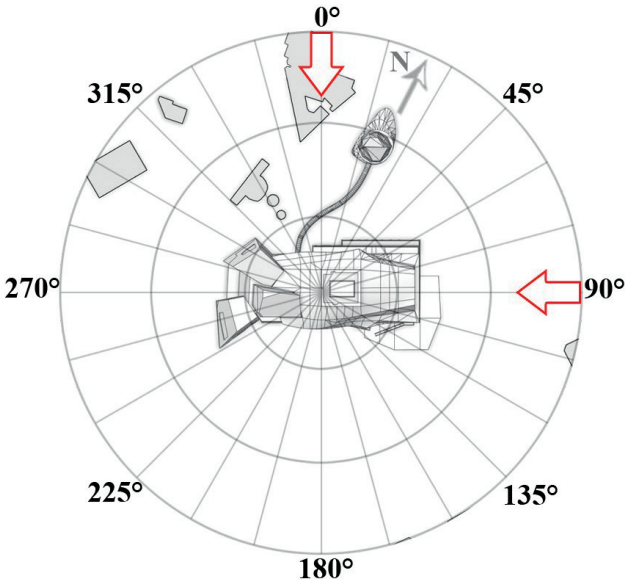


Figure 2. Investigated wind directions

2.2. Mathematical models

In this study, urban wind flow is simulated using time-averaged (RANS) incompressible and isothermal Navier-Stokes equations. Such assumptions regarding the flow are known to be justified and accepted by researchers for determination of snow loads on roofs [10]:

$$\frac{\partial \overline{u}_i \overline{u}_j}{\partial x_j} = -\frac{1}{\rho}\left(p + \frac{2}{3}\rho k\right) + \\ + \frac{\partial}{\partial x_j}\left((\nu + \nu_t)\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right)\right), \qquad (2)$$

where $\overline{u}_i$ are the components of the averaged flow velocity, [m/s]; t is the time, [s]; $\bar{p}$ is the av-

eraged pressure, [Pa]; ρ = 1.225 kg/m^3 is the density of air; $\nu = 1.46 \cdot 10^{-5}$ m^2/s is the kinematic viscosity of air; and ν_t is the turbulent viscosity.
The continuity equation is given as:

$$\frac{\partial \overline{u_j}}{\partial x_j} = 0 \quad (3)$$

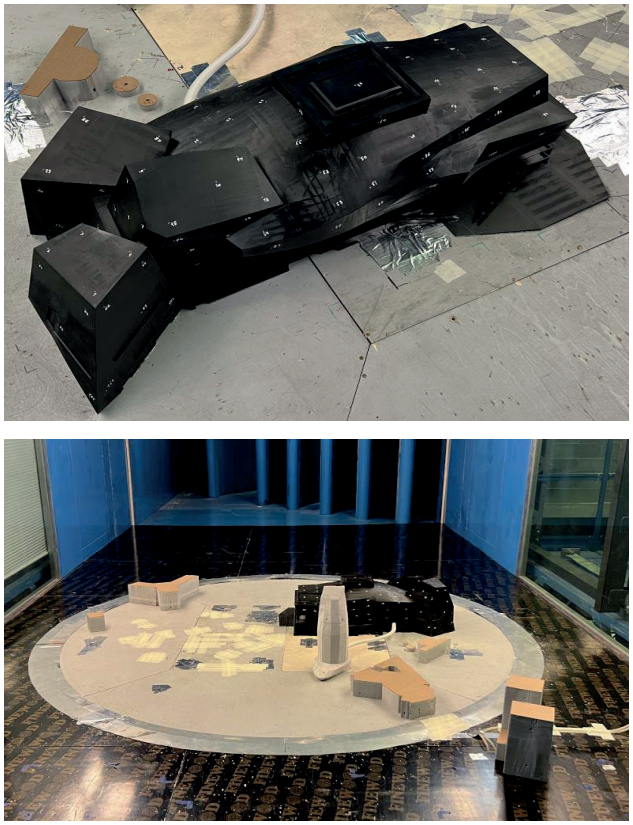


Figure 3. The Kemerovo MTEC model in the MSUCE WT

The following turbulence models are considered:
– *k*-ω Shear-Stress Transport (*k*-ω SST) is a general two-parameter model which switches between the regular *k*-ω model near the walls and the *k*-ε model in the free flow via a mixing function;
– Generalised *k*-ω (GEKO) is a modification of the regular *k*-ω model, which allows for adjusting to different types of flows by tweaking a number of dimensionless parameters exposed to the user. In this study, only the C_{SEP} is varied (between 0.70 and 1.25), which governs flow separation and adverse pressure gradients.

2.3. CFD setup

To provide a correct comparison between the results of numerical and physical modelling, the CFD model needs to reproduce all the major parameters of the experiment, such as scale, WT's working area dimensions, and boundary conditions.
The numerical geometry of the Kemerovo MTEC with the surrounding buildings corresponds to the experimental one (Fig. 4).

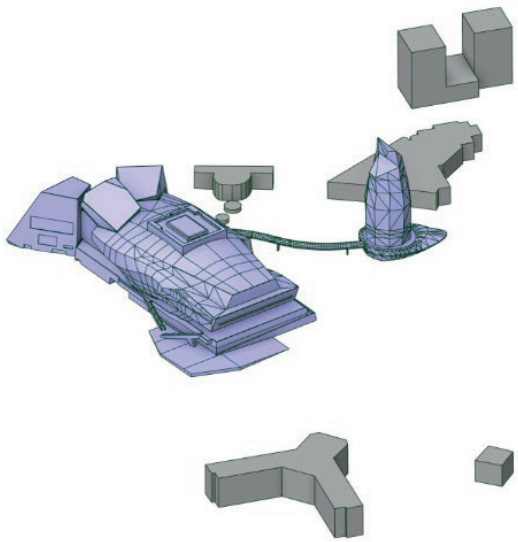
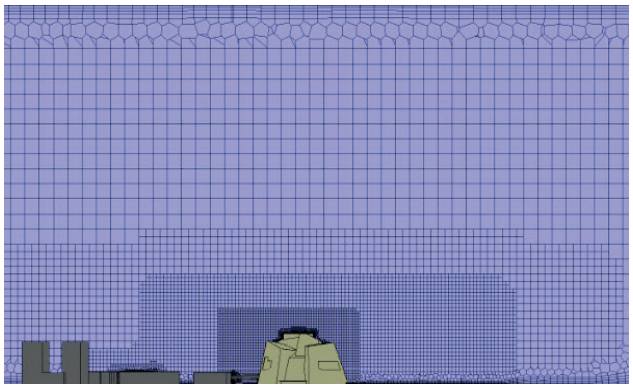


Figure 4. Numerical geometry of the Kemerovo MTEC with the surrounding buildings

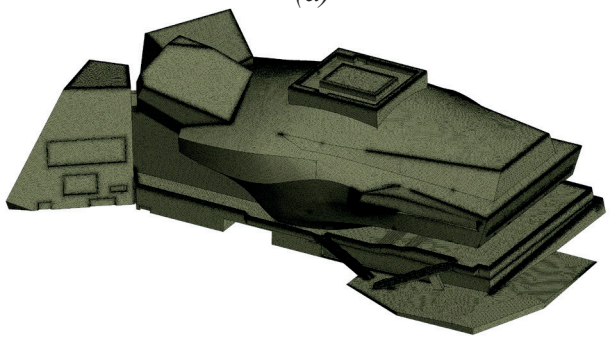
Polyhexcore finite-volume meshes were used in this study, combining polygonal, prismatic and hexagonal cells. Three meshes were developed to perfrom the grid convergence study, a coarse one (4.99 million cells), a medium one (10.77 million cells), and a fine one (19.06 million cells). The meshes differ in face size by factors of 1.5 (coarse to medium) and 1.33 (medium to fine). Each mesh has 5 prism layers parallel to the surfaces at the bottom and 10 layers at the target building, ensuring $y+ \leq 5$ for the building's roof surfaces for all the grids.
The boundary conditions are shown in Fig. 6:
– at the inlet, the flow velocity and the turbulent intensity profiles are interpolated from WT experimental data (Fig. 7). Two flow regimes are investigated, with the velocity at 0.05 m (scaled) equal to 3 m/s or 6 m/s (labelled as V3 and V6, respectively);

– at the outlet, the gauge pressure is set to 0;
– the rest of the surfaces are no-slip walls.

The coupled velocity-pressure solver was used, with 2nd order schemes for the momentum, turbulent transport and pressure equations. The total number of iterations was set to 300, of which the last 140 were calculated with high-order relaxation enabled. Data sampling was performed for the last 120 iterations.



(a)



(b)

Figure 5. Finite-volume mesh: a – in the longitudinal section of the domain; b – on the surface of the Kemerovo MTEC

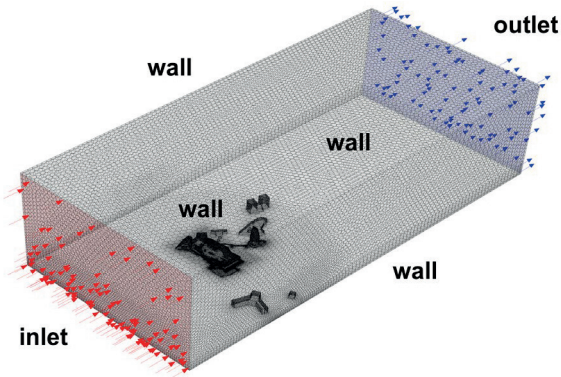


Figure 6. Boundary conditions

A total of 36 3D steady-state runs (2 angles of attack × 2 velocities × 3 turbulence models × 3 meshes) were performed.

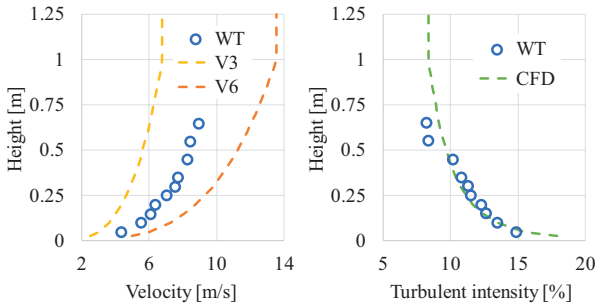


Figure 7. Velocity [m/s] *and turbulent intensity* [%] *profiles from WT measurements and CFD approximations*

2.4. Verification & Validation methods

Previous research [21] on the case of the Kemerovo MTEC has revealed that some widely used error estimation methods, such as Richardson extrapolation and approximate error spline, may display incorrect behaviour in convergence analysis. Therefore, a simpler error estimation method was used in their stead for this study.

Grid convergence was estimated as a ratio of the wall shear stress's range to its mean, which is then interpolated to the coarse grid for comparison:

$$e_g = \left| \frac{\max\limits_i \tau_{w,i} - \min\limits_i \tau_{w,i}}{2 \operatorname{mean}\limits_i \tau_{w,i}} \right| 100\%, \qquad (4)$$

where i denotes the grid (1 – coarse, 2 – medium, 3 – fine), and the values of $\max(\tau_{w,i})$, $\operatorname{mean}(\tau_{w,i})$ and $\min(\tau_{w,i})$ are taken from the sampled datasets at each node of the facility's roof mesh.

Iteration convergence was estimated similarly:

$$e_{it} = \left| \frac{\max\limits_k \tau_{w,k} - \min\limits_k \tau_{w,k}}{2 \operatorname{mean}\limits_k \tau_{w,k}} \right| 100\%, \qquad (5)$$

where $\tau_{w,k}$ are the wall shear stress values at the k^{th} iteration (k = 181...300).

For $\operatorname{mean}(\tau_{w,k}) \approx 0$, the values of e_{it} take very large values, not characterising convergence. In

such cases, formula (5) is not applicable and the corresponding points are discarded.
Since the experimentally obtained values of numerical shape coefficient μ_{nm} and physical shape coefficient μ_{pm} are not exactly equal to the values of design shape coefficient μ (and, generally, to each other), the simulations' results are compared qualitatively in the first place. This is due to the nature of the methodologies that are used to simulate snow deposition and snow transport in WTs and CFD.

3. RESULTS AND DISCUSSION

This section presents the results of grid and iteration convergence for the numerical modelling, and the comparison of snow deposit maps obtained numerically and physically.
The following nomenclature is used:

Table 1. Numerical results nomenclature

Parameter		*Value*	*Abbr.*
Configuration	*Angle of attack*	0°	A0
		90°	A90
	Turbulence model	GEKO-0.70	G070
		GEKO-1.25	G125
		k-ω SST	kwSST
	Flow velocity	3 m/s	V3
		6 m/s	V6
Grid quality		Coarse	M1
		Medium	M2
		Fine	M3

3.1. Iteration convergence

For the most runs (24 out of 36, see Fig. 8, 9) the mean values of e_{it} are well below 7%, except for A0-G125 ($7.6\% \leq e_{it} \leq 15.9\%$) and A0-kwSST ($38.3\% \leq e_{it} \leq 76.3\%$). Still, even the runs with the overall lowest values of e_{it} demonstrate local areas of extremely high e_{it} (Fig. 11). However, the plotted values of $\tau_{w,k}$ in such areas reveal oscillatory convergence (Fig. 12). This result underlines the necessity of data sampling for simulations with complex geometry and skewed cells, whose presense in meshes oftentimes cannot be avoided.

3.2. Grid convergence

For the most configurations (10 out of 12, see Fig. 10) the mean values of e_g are well below 9%. The lowest values are obtained with G070 ($4.98\% \leq e_g \leq 6.74\%$), followed by G125 ($5.53\% \leq e_g \leq 7.56\%$) and, finally, kw-SST ($7.97\% \leq e_g \leq 26.2\%$). Just as with e_{it}, the configurations with the overall lowest values of e_g demonstrate local areas of extremely high e_g (Fig. 13). However, the plotted contours of such high value areas reveal that their area remains relatively small (i.e., for the A90-G070-V3 configuration $e_g \geq 10\%$ for only 11% of the total surface area). This result shows that GEKO-0.70 allowed for the best grid convergence between the three turbulence models used in this study.

3.3. Comparison between numerical and physical results

Based on the convergence study, GEKO-0.70 results were used for the comparison with physical snow deposit maps, since it produced the overall lowest values of e_{it} and e_g. Numerical snow deposit maps are presented for all three grids to demonstrate how the deposit contours change with grid refinement.
Qualitative comparison between the numerical and the physical simulations' results for two angles of attack show good agreement both in general and locally, sufficient enough to be used in conjunction with the building code provisions to produce maps of the design shape coefficient μ.

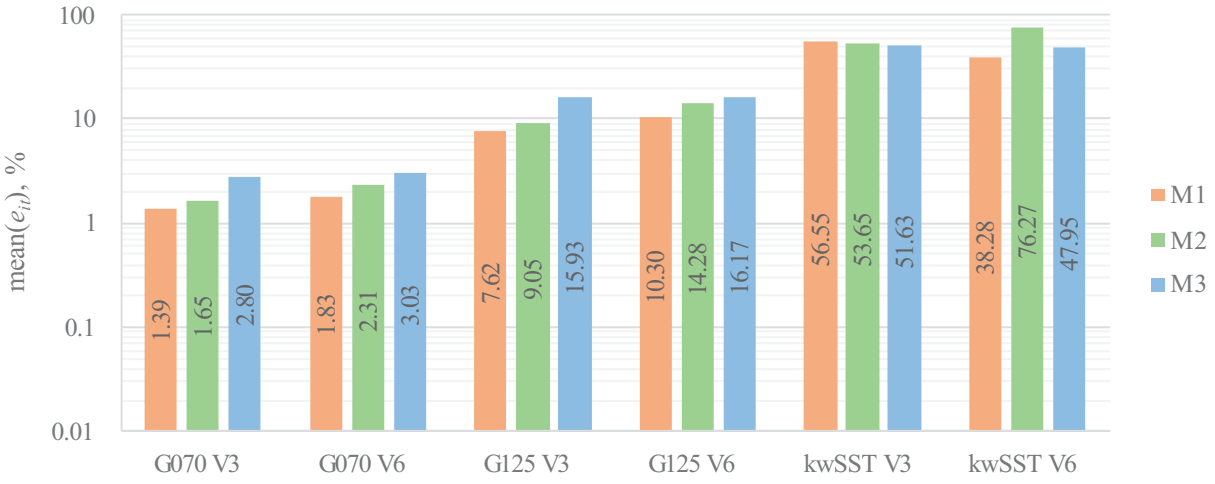


Figure 8. Mean iteration error e_{it} [%] for different grids, angle of attack 0°

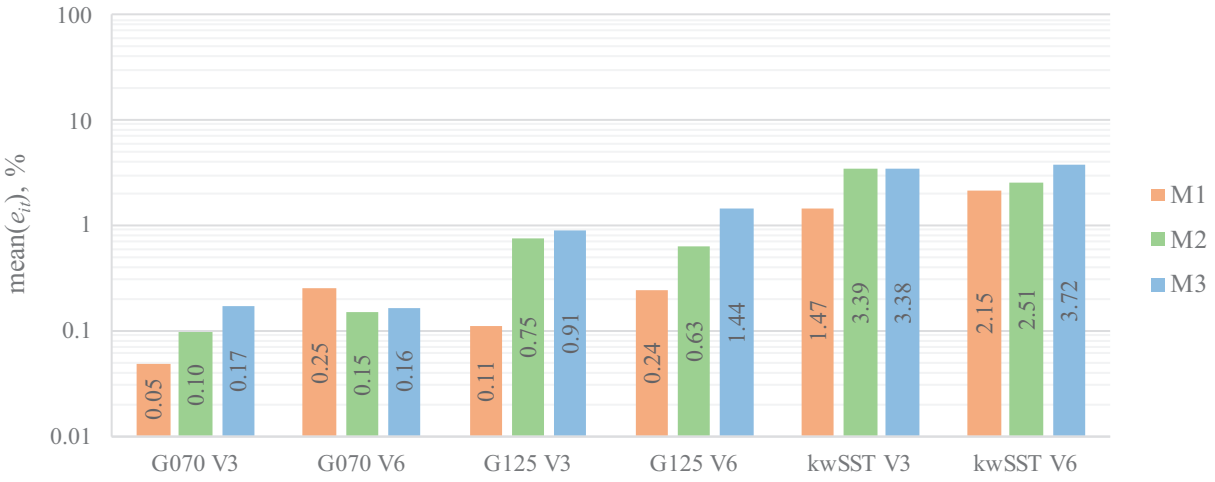


Figure 9. Mean iteration error e_{it} [%] for different grids, angle of attack 90°

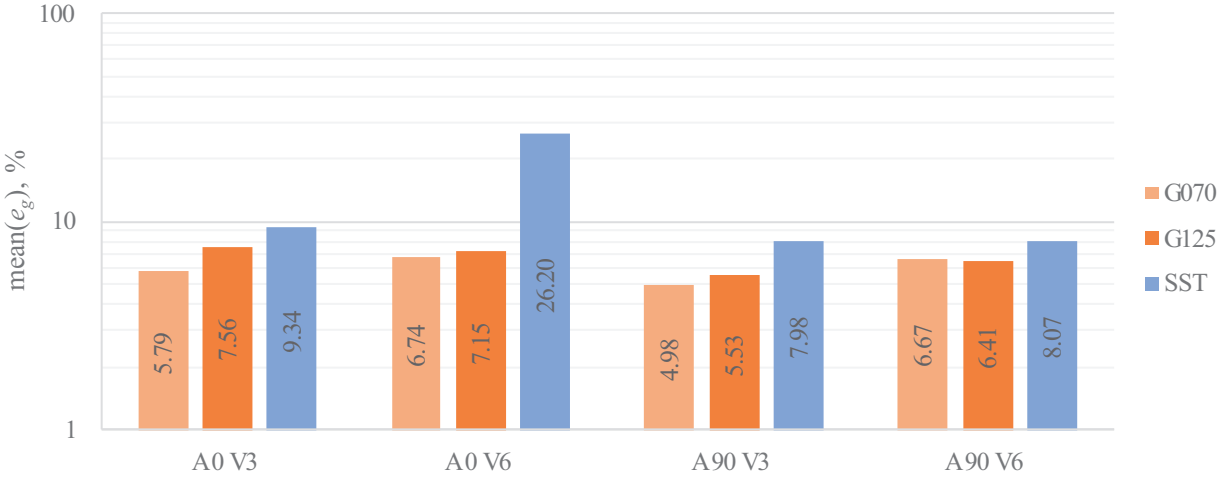


Figure 10. Mean grid error e_g [%] for different turbulence models

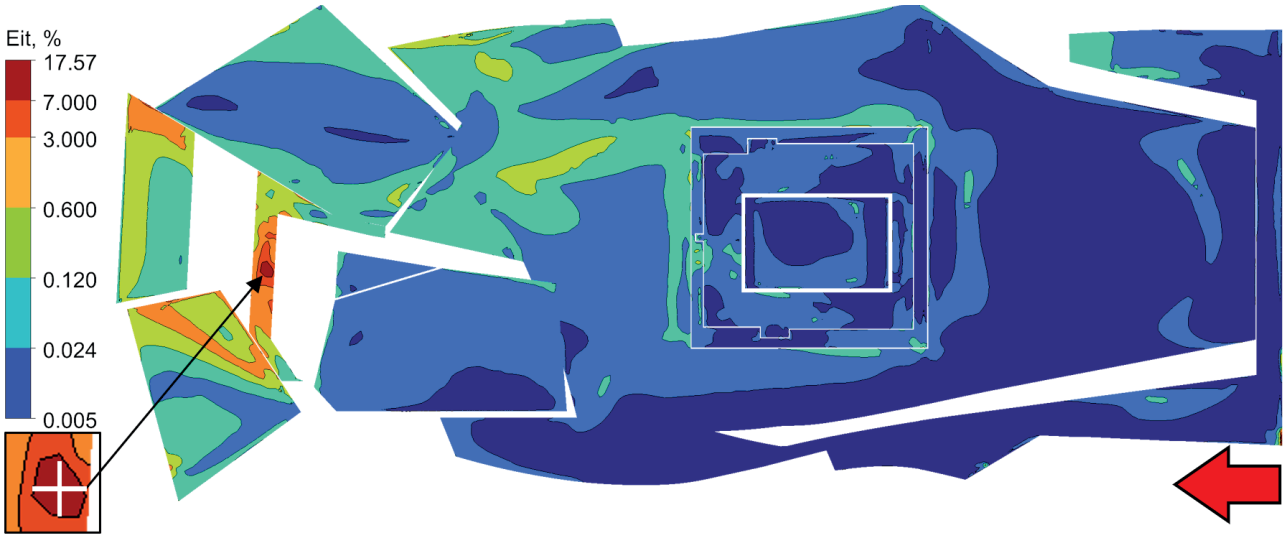


*Figure 11. Iteration error e_{it} [%] for **A90-G070-V3-M1** case, log scale*
Angle of attack is shown with the red arrow
The mark depicts the cell centroid with the highest e_{it} value

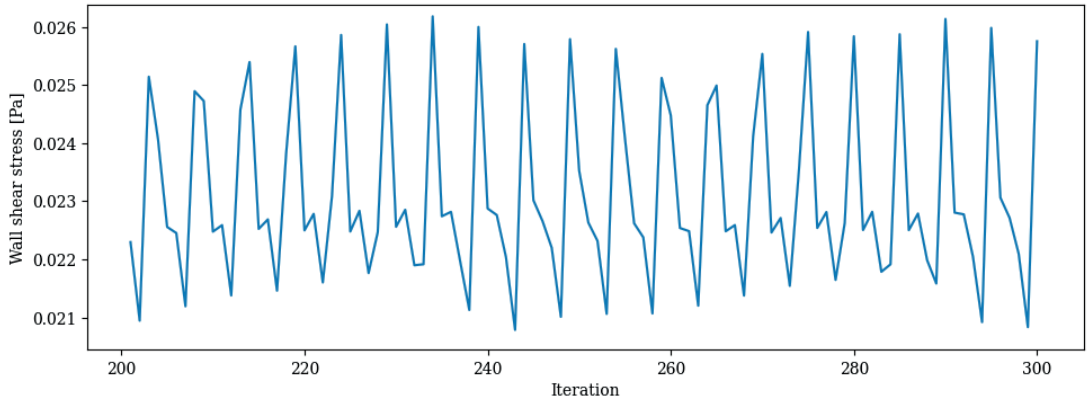


Figure 12. Wall shear stress [Pa] *plot in the aforementioned cell centroid over the last 100 iterations reveals oscillatory convergence*

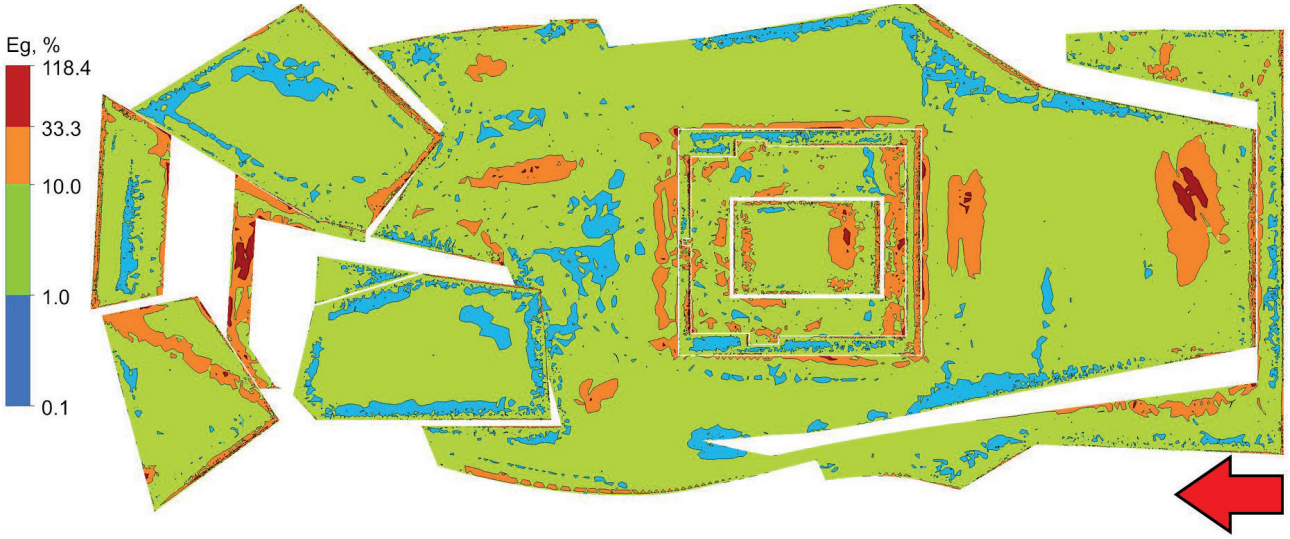
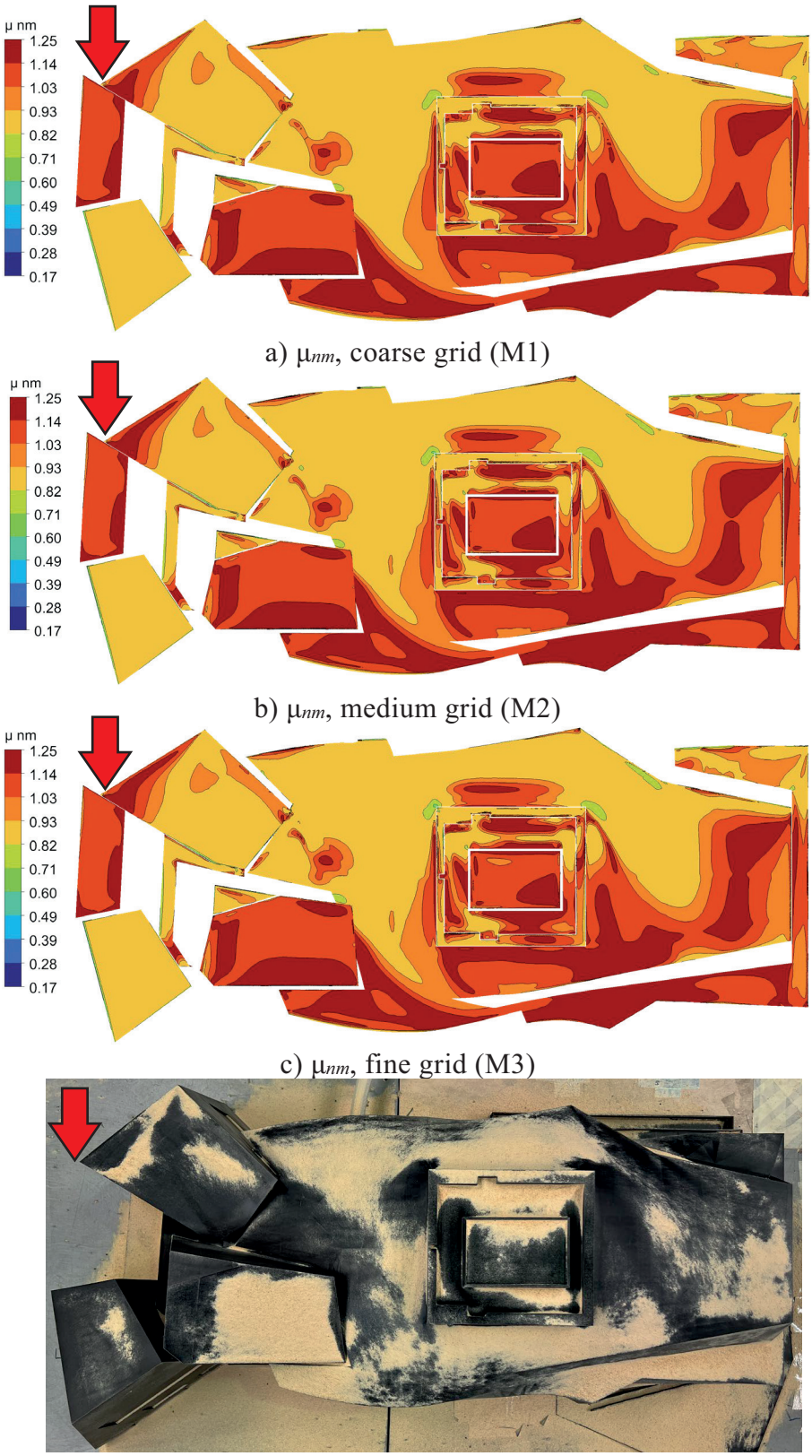


*Figure 13. Grid error e_g [%] for **A90-G070-V3** configuration, log scale*



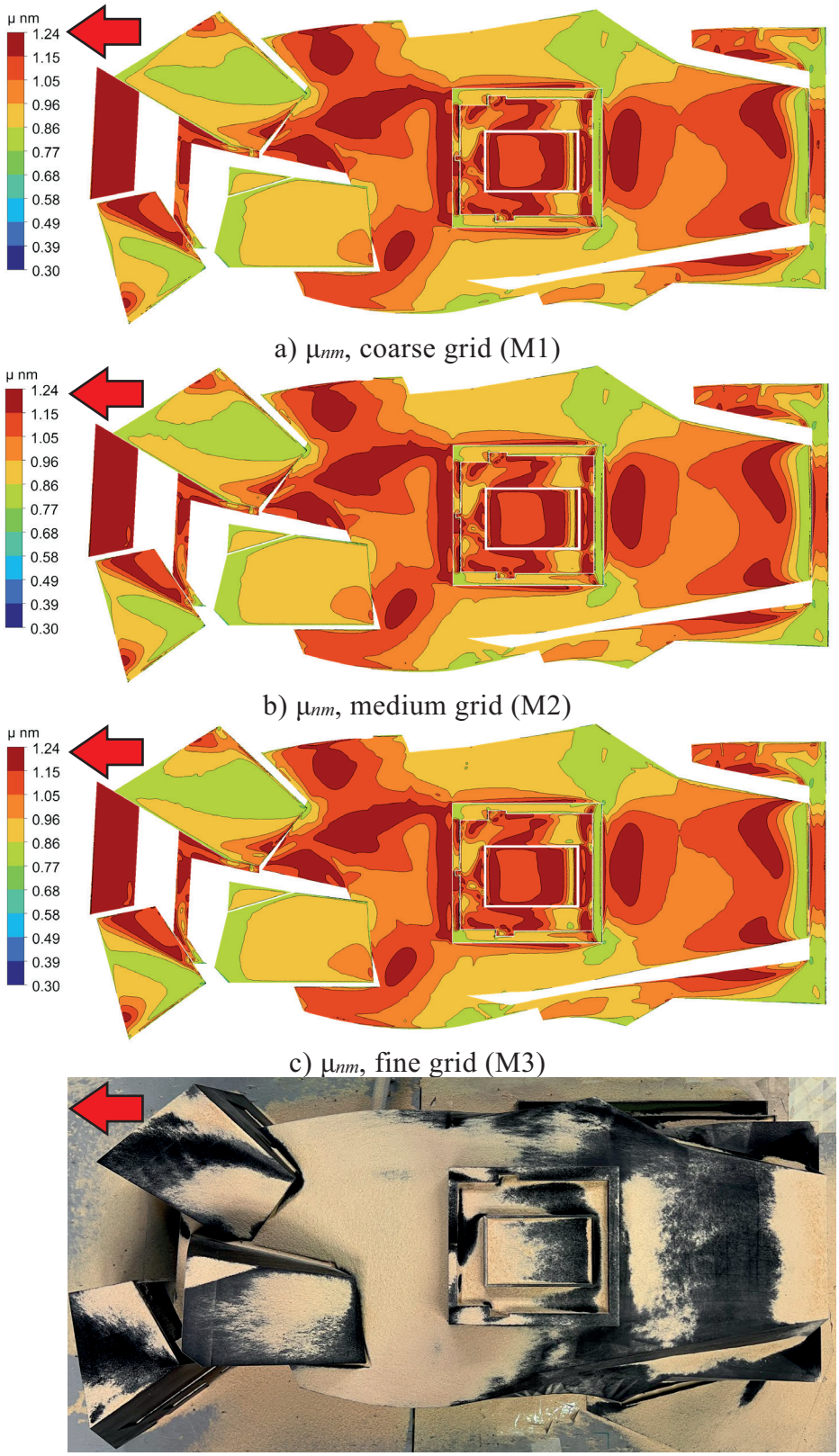
a) μ_{nm}, coarse grid (M1)

b) μ_{nm}, medium grid (M2)

c) μ_{nm}, fine grid (M3)

d) μ_{pm}

Figure 14. Numerically modelled shape coefficient μ_{nm} vs. physically modelled shape coefficient μ_{pm} Angle of attack 0°, GEKO-0.70



a) μ_{nm}, coarse grid (M1)

b) μ_{nm}, medium grid (M2)

c) μ_{nm}, fine grid (M3)

d) μ_{pm}

Figure 15. Numerically modelled shape coefficient μ_{nm} vs. physically modelled shape coefficient μ_{pm} Angle of attack 90°, GEKO-0.70

4. CONCLUSIONS

The following conclusions are made from the conducted research:

1. Numerical models of the Kemerovo MTEC and the surrounding buildings have been developed. A total of 2 wind directions, 2 velocities, 3 levels of grid refinement (4.99, 10.77 and 19.06 million cells) and 3 turbulence models (k-ω SST, GEKO-0.70 and GEKO-1.25) were considered.

2. A thorough **verification** has been carried out to investigate the iteration and grid independence of the solution:

- Iteration and grid error can contribute significantly to the numerical solution results. To minimise this effect, it is necessary to use data sampling and maintain good mesh quality.
- The solution for all the turbulence models mostly demonstrates oscillatory behaviour on different grid refinement levels.
- The k-ω SST model shows the worst iteration and grid convergence among the studied models.
- The GEKO models show significantly better iteration convergence (e_{it} < 16.2%), and decreasing the C_{SEP} further improves it (e_{it} < 3.5% for C_{SEP} = 0.70).
- The best grid convergence is achieved with GEKO-0.70 (e_g < 7%) and the worst with k-ω SST (e_g > 8%).

3. A thorough **validation** has been carried out through a qualitative comparison of the numerical (CFD) and physical (WT) modelling results.

- The GEKO turbulence model with the parameter C_{SEP} = 0.70 displayed good agreement with the experimental data. This model is recommended for use in snow load determination for long-span roofs in steady-state simulations.

4. It is confirmed that Ansys Fluent allows the snow loads determination on buildings of complex shape with the accuracy sufficient enough for practical purposes, provided that modern turbulence models and methods set out in the STO [13] are used.

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