Vortex formation and heat transfer in the system of building models at turbulent separated flow

S Korobkov\textsuperscript{1*}, A Gnyria\textsuperscript{1}, A Dyogin\textsuperscript{1}, M Sokol\textsuperscript{1} and V Terekhov\textsuperscript{2}

\textsuperscript{1}Tomsk State University of Architecture and Building, Russia
\textsuperscript{2}Kutateladze Institute of Thermophysics SB RAS, Russia

*E-mail: korobkov_1973@mail.ru

Abstract. The article presents the results of the study of vortex formation and integral heat exchange in the air flow around the building model system. The experimental setup, measurement methods, results and their analysis are described. The analysis of the phenomena specific for the given model configuration at different mutual model arrangements is presented.

1. Introduction

Studying air flows around of the system of urban buildings is a complex and multi-factor problem. Their different positioning in microdistricts and districts results in variation of aerodynamic flow patterns, distribution of pressure fields, and heat transfer in individual buildings, which is complicated by the presence of separated flows interacting with each other. The vast amount of information in the field of aerodynamics of engineering structures largely covers the needs in modern design techniques.

However, the interference of wind flows and its influence on the heat exchange of buildings at their different locations remains poorly studied. The works [1–10] show that the formation of separated flows at streamlining of three-dimensional obstacles, namely, buildings of different shapes and heights, is one of the most difficult cases that currently resist sufficiently accurate numerical modeling.

The aim of this paper is an experimental study of the integral heat exchange in the air flow around the system of three buildings with variations in their location, Reynolds number and angles of attack. The work objectives are studying experimentally the external aerodynamics and heat transfer of groups of buildings and obtaining data for subsequent verification of computational methods, intended for the design of urban development with the aim of reducing heat loss and ensuring the safety and comfort of urban environment. This work continues the research presented in [11–13].

2. Experiment

Series of experiments were conducted at the aerodynamic laboratory stand of the Chair of COT of TSACU, consisting of a wind tunnel with a working chamber with a cross section of 0.32×0.21 m and a length of 0.9 m, experimental models and measuring equipment (figure 1).

The integral heat exchange for a group of three models of buildings with a relative height $H/a = 3$ and 5, as well as their characteristic features in the variation of their location relative to each other, were studied. The experiments were carried out based on the following principles: two obstacle models were located upstream and created turbulent separated flows, which influenced the aerodynamic
structure of the third model under study, located downstream (figure 2). Such arrangement of models is one of the widespread options of block building design solutions.

The caliber change between the front obstacle models "1" and "2" was $L1/a = 1; 2; 3$ (transverse displacement). The studied model "3" was located in the wake at a distance from the front obstacles of $L2/a = 2; 4; 6; 8$ and 10 (longitudinal displacement).

The angle of attack of the air flow was taken as $\varphi = 0^\circ$ and $45^\circ$. The air flow velocity was 9.4; 18.8 and 28.4 m/s, and Reynolds number, calculated by the size of the prism face $Re = U_0 \times a / \nu = 1.87 \div 5.65 \times 10^4$. The air flow velocity was changed by speed control system, using a frequency converter. The heat exchange was measured behind standing model "3" (thermal model), at that the front models "1" and "2" were not heated. Temperature was determined on the thermal model, using HC thermocouple with $d = 0.2$ mm, caulked in the measuring face of the model. Thermocouples were installed vertically and horizontally. The number of sensors on the measuring side of the model with a relative height $H/a = 3$ equals 13 pcs; and for $H/a = 5–19$ pcs (figure 3).

3. Results and discussions

At the first stage, data on visualization of the structure of separated flows were obtained at streamlining of the system of building models by applying the soot-oil-based mixture to the lower wall of the channel (figures 4–5). All models in these experiments were made of Plexiglas with a thickness of 5 mm.

The aim of visualization studies was to establish the relationship between the obtained patterns of air flow around the system of building models with the pattern of distribution of heat transfer coefficients $\alpha$, as well as to evaluate the hydrodynamic structure of separated flows and the nature and size of separated zones.

![Figure 1. General view of the aerodynamic stand](image)

![Figure 2. Layout of experimental models in the air flow: a) – the angle of attack of the airflow $0^\circ$, b) – the angle of attack of the airflow $45^\circ$; a – the transverse size of the models, $a = 30$ mm; $L1$ – the transverse distance between the models, mm; $L2$ – the distance between the transverse group of obstacles (model "1" and "2") and the studied model “3”](image)
As can be seen from figure 4a, at small distances between prisms \((L1/a = 1\) and \(L2/a = 2\)) the separated flows between models "1" and "2" merge into the total accelerated flow due to their contraction and influence the model "3". On the front face of the model "3", there is a strong flow deceleration without the formation of a horseshoe vortex, characteristic of the front models "1" and "2". However, there is a strong influence of the arch-like vortices, formed in an after zone behind models "1" and "2" characteristic of stagnant zones. A similar phenomenon is observed behind the
model "3", but its wakes go far beyond its edges. The detected wakes of vortices (recirculation zones) with periodic pulsations, formed near the lateral faces, are much larger than in models "1" and "2". This indicates that the side faces of the model "3" are located in the zone of intense turbulent flow. All the above testifies to the action of the air flow with a velocity that is larger than the flow velocity, i.e. the merger of two separated flows leads to the formation of an accelerated air jet between the models, affecting the model "3".

With an increase in transverse displacement \( L_1/a \) to 3 calibers (figure 4) the effect of interference of the air flow, emerging between the models "1" and "2," decreases. The horseshoe contours on the front faces of the models "1" and "2" cover no more than \( L_1/4 \) in the transverse channel between them. Contours of the horseshoe vortex begin to appear on the front face of the model "3". Model "3" is subjected only to the action of the rarefied zones behind models "1" and "2". Each of the front models has its own clear picture of the flow, typical for single models.

With the increase in the distance \( L_2/a \) from 2 to 10 calibers (figures 4, b and 4, d) the zone of stable influence of the horseshoe vortex behind the front models in the area between the model system is gradually blurred. The pattern of the air flow around the model "3" approaches the pattern of streamlining of the front models "1" and "2", and, therefore, a single model.

In this case, one may clearly observe the same flow regimes as in the case of air flow around the single front model.

Similar phenomena are observed at streamlining of a group of three models at an air attack angle of 45 degrees (figure 5). The flow regime here is wedge-shaped.

Figure 5. Visualization of the air flow in the vicinity of a group of three models with angle of attack of 45 degrees: a) \(- L_1/a = 1, L_2/a = 2\); b) \(- L_1/a = 1, L_2/a = 10\); c) \(- L_1/a = 3, L_2/a = 2\); d) \(- L_1/a = 3, L_2/a = 10\)
maximum integral heat exchange is observed at the caliber $L_2/a = 8$ on the side faces, and with an increase in the distance to $L_2/a = 10$ there is a decrease in the heat exchange of the model "3". In this case, the air flow pattern and the distribution of the heat transfer coefficient along the faces of the model "3" standing behind, approaches a stand-alone prism.

4. Conclusion
It is shown that the separated flow structure directly affects the nature of changes in the integral heat transfer and wind pressure. One of the main features is the presence of vortex zones between three prisms modeling the system of buildings. With the increase in $L_1/a$ and $L_2/a$ scales, according to visualization tests, the influence of vortex zones on the model "3" from the models "1" and "2" weakens, which leads to the air flow flattening, and as a result should lead to a better renewal of stagnant mass and, consequently, a change in the heat exchange processes. At that the streamlining pattern of the model standing behind approaches the stand-alone prism.

The obtained results will complement the known data of both domestic and foreign researchers in the field of heat exchange and architectural aerodynamics at streamlining a group of buildings that model the block construction. As a result, the optimal arrangement of buildings in block construction can reduce the number of blown (permeable) areas and reduce heat loss in buildings and structures.

Acknowledgement
The research executed at IT SB RAS was financially supported by the Russian Science Foundation (grant No. 18-19-00161), while research works at TSUAB were funded by the Russian Foundation for Basic Research (grant No. 18-08-01025).

References
[1] Aliaga D A, Lamb J P, Klein D E 1994 Convective heat transfer distributions over plates with
square ribs from infrared thermography measurements Int. J. Heat Mass Transfer 37(3) 363–74

[2] Meinders E R, Hanjalic K 1999 Vortex structure and heat transfer in turbulent flow over a wall-mounted matrix of cubes Int. J. Heat and Fluid Flow 20 255–67

[3] Martinuzzi R J, Havel B 2000 Turbulent flow around two interfering surface-mounted cubic obstacles in tandem arrangement J. Fluids Engineering 122 24–31

[4] Valensia A, Martin J S, Gormaz R 2001 Numerical study of the unsteady flow and heat transfer in channels with periodically mounted square bars Int. J. Heat and Mass Transfer 372 65–70

[5] Meinders E R, Hanjalic K 2002 Experimental study of the convective heat transfer from in-line and staggered configuration of two wall-mounted cubes Int. J. Heat and Mass Transfer 45 465–82

[6] Britter R E, Hanna S R 2003 Flow and dispersion in urban areas Annu. Rev. Fluid Mech 35 469–96

[7] Popovac M, Hanjalic K 2006 Vortical structure and heat transfer on a jet-impinged wall-mounted cube in a cross-flow Turbulence, Heat and Mass Transfer 5 1–11

[8] Ming Gu M, Xie Z-N 2011 Interference effects of two and three super-tall buildings under wind action Acta Mech. Sin. 27(5) 687–96

[9] Kim W, Tamura Y, Yoshida A 2015 Interference effects on aerodynamic wind forces between two buildings J. Wind Eng. Ind. Aerodyn. 147 186–201

[10] Lankadasu A, Vengadesan S 2008 Interference effect of two equal-sized square cylinders in tandem arrangement: With planar shear flow Int. J. Numer. Meth. Fluids 57 1005–21

[11] Gnyria A I, Korobkov S V, Dyogin A G, Sokol M M, Koshin A A and Terekhov V I 2016 Results of the investigation fluid flow around a group of three building models under interference conditions Vestnik of TSUAB 6 201–08 (in Russian)

[12] Gnyria A, Korobkov S, Koshin A, Terekhov V 2017 Aerodynamic and thermal interference of turbulent separated flows over building models MATEC Web of Conferences 115 02002

[13] Korobkov S.V., Deogin A.G., Sokol M.N., Gnyria A.I., Terekhov V.I., Fayskanov T.M. 2017 The influence of calibers between poorly flowing bodies in the group on the regularities of integral external heat transfer with the aim of improving the energy efficiency of external enclosing structures of buildings Energy and Resource Efficiency of Low-Rise Residential Buildings: Proc. III Russian Conf. with Intern. Participation, Novosibirsk, March 21-23 (Novosibirsk: Publ. House of the Institute of Thermophysics SB RAS) 333–37 (in Russian)