Development of air exchanging system for subsonic wind tunnel

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Abstract. The study analyzes main ways of air flow cooling in closed-circuit wind tunnels (subsonic and transonic): subject to air exchange (continuous partial exhaust of warm air and its change for colder outside air) and by means of the use of liquid-coolant stationery heat exchanger. It is shown that additional equipment is not required when applying air exchange to cool the flow and, in general, it can reduce costs of wind tunnel maintenance and, consequently, test prices. Based on an example of subsonic wind tunnel designed in TsAGI the evaluation of gas-dynamic and thermo-dynamic circuit flow properties are evaluated. The study also proposes options of air exchange arrangement for high-power operations at \( w=160 \text{ ms}^{-1} \) in closed test section provided that the outside air temperature is \( T_f=20^\circ \text{C} \). The paper represents the results of numerical simulation for air flow in the segments of wind tunnel duct in presence of air exchange holes.

1. Introduction

Duct air in a closed-throat test section of subsonic closed-circuit wind tunnel can be exposed to significant heat. However, a proper aerophisical experiment (minimising instrumental error of measuring equipment) requires near-even temperature conditioning in the wind tunnel, thereat test section flow temperature should be \( T\leq40^\circ \text{C} \). Thus, one of urgent issues when designing TsAGI subsonic wind tunnel is arrangement of air cooling.

The specifications of new subsonic wind tunnel are as follows: dimensions 130×50 m, test section cross section 5.5×7.5 m, maximum flow rate \( w=140 \text{ ms}^{-1} \) in open test section and \( w=160 \text{ ms}^{-1} \) in closed test section, compressor power according to preliminary estimations will be about \( N\approx30 \text{ MW} \).

Calculations and design studies have showed that a steady-state heat exchanger in the wind tunnel circuit incurs considerable construction costs and operation expenses [1]. Therefore an alternative way is considered for cooling the flow by means of air exchange between the wind tunnel and the environment.

As part of the air exchange arrangement study for the considered subsonic wind tunnel, main gas-dynamic and thermal characteristics of flow in duct segments, mass airflow of surrounding air for cooling, configurations of air exchange holes, and compressor required power are determined.

2. Calculation of flow gas dynamic and thermal parameters in segments of subsonic wind tunnel duct

For the calculation of air exchange system it is necessary to evaluate main gas dynamic and thermal parameters of flow in wind tunnel segments. Figure 1 represents the initial circuit of concerned wind tunnel, where 1 is the settling chamber; 2 is the air cooler; 3 is the honeycomb; 4 is the turbulence...
screens; 5 is the nozzle; 6a, 6b is the open and closed test sections; 7 is the collector; 8 is the first diffuser; 9, 11, 15, 16 are corners; 10 is the second diffuser; 12 is the safety screen; 13 are fans; 14 is the third diffuser; 17 is the wide-angle diffuser; 18 is the screen; 19 is the acoustic chamber; 20 is the acoustic blanket; 21 is the external balance support device; 22 is the turning mechanism; 23 is the internal balance support device.

Figure 1. Schematic diagram of subsonic wind tunnel.

Limiting case was elaborated, namely wind tunnel operation at extreme mode at a speed \( w_{ts} = 160 \text{ms}^{-1} \) in the closed test section and the ambient air temperature \( T_f = 20 ^\circ \text{C} \).

If in the first approximation thermal losses, heat of additional equipment and the model are neglected, total compressor power is:

\[
N = c_p G \Delta T_0 ,
\]

where \( c_p \) is the mass isobaric heat capacity of air; \( G \) is the mass air flow; \( \Delta T_0 \) is the total air temperature change after the compressor.

Mass air flow is:

\[
G = \rho_{ts} F_{ts} w_{ts} ,
\]

where \( \rho_{ts} \) is the air density; \( F_{ts} \) is the area section; \( w_{ts} \) is the flow velocity at the inlet of test section.

Air density in the test section is expressed through the density in the stagnation point:

\[
\rho_{ts} = \rho_0 \frac{1}{\left[1 + \frac{\kappa - 1}{2} \left( \frac{w_{ts}}{a} \right)^2 \right]^{1/2}} ,
\]

where \( \kappa \) is the heat capacity ratio (for air \( \kappa = 1.4 \)); \( a = 20 \cdot 10^5 \) is the local speed of sound.

Thus, mass air flow in wind tunnel duct (if there is an air exchange system – airflow rate in the test section) equals to \( G = 6806.9 \text{ kgs}^{-1} \).

Based on the equations stated in works [2 – 4] the evaluation is made for hydraulic resistance coefficients, total pressure losses, flow rate, total and static temperature (at the inlet of considered
segment) (see Table 1). Initial temperature at the inlet in the test section is taken to be equal to \( T=35 \, ^\circ\text{C} \).

**Table 1. Evaluation of flow parameters in subsonic wind tunnel segments**

| Wind tunnel segment       | \( \xi \) | \( \Delta p, \text{ Pa} \) | \( N, \text{ W} \) | \( w, \text{ m/s} \) | \( T, \, ^\circ\text{C} \) | \( T_p, \, ^\circ\text{C} \) |
|---------------------------|----------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Test section              | 0.042    | 661             | 4956            | 160.0           | 35.0            | 47.7            |
| Diffuser 1                | 0.029    | 316             | 2296            | 133.1           | 38.9            | 47.7            |
| Corner 1                  | 0.175    | 518             | 3577            | 69.4            | 45.3            | 47.7            |
| Diffuser 2                | 0.009    | 27              | 184             | 69.4            | 45.3            | 47.7            |
| Corner 2                  | 0.175    | 356             | 2442            | 57.5            | 46.1            | 47.7            |
| Compressor chamber (+protective net) | 0.209 | 425             | 2916            | 57.5            | 46.1            | 47.7            |
| Diffuser 3                | 0.019    | 14              | 95              | 34.4            | 51.3            | 51.9            |
| Corner 3                  | 0.254    | 119             | 807             | 27.6            | 51.5            | 51.9            |
| Wind tunnel section       | 0.005    | 2               | 16              | 27.6            | 51.5            | 51.9            |
| Corner 4                  | 0.254    | 119             | 807             | 27.6            | 51.5            | 51.9            |
| Diffuser 4 (+ net)        | 0.984    | 461             | 3125            | 27.6            | 51.5            | 51.9            |
| Stilling chamber (+honeycomb, field meshes) | 2.624 | 418             | 2837            | 16.1            | 51.8            | 51.9            |
| Air cooler                | 3.380    | 539             | 3659            |                 |                 |                 |
| Nozzle                    | 0.002    | 32              | 236             | 16.1            | 47.6            | 47.7            |
| Total                     | 4426     | 27953           |                 |                 |                 |                 |

Specific drag of wind tunnel is calculated by the formula:

\[
\xi = \sum \xi \left( \frac{w_i}{w_{is}} \right)^2
\]  

and it is equal to \( \xi=0.254 \).

Further calculations show that thermal losses of heat transition through wind tunnel walls will be less than 4.1% of designed capacity of the compressor if this thermal mode is implemented.

Thus, in further calculations we do not consider thermal losses of heat transition.

3. **Calculation of main parameters of air exchange system**

Two options of air exchange hole positions are considered.

In the first option the inlet neck is located in the midsection of the second diffuser (before the compressor where there is low-pressure area with respect to atmospheric static pressure); the outlet neck is located in the midsection at the wind tunnel segment between corners 3 and 4 (after the compressor where there is high-pressure area with respect to atmospheric static pressure).

Tempering mass air flow was calculated by the equation of thermal balance. Inflow and outflow rates through holes were calculated with the assumption of adiabatic expansion process to low static pressure area.

However, larger mass air flow in the wind tunnel duct entails more pressure losses in the circuit and, consequently, the need of higher compressor power.

Converging solution was obtained in case if the static temperature at the inlet of closed test section has the value of \( T=35 \, ^\circ\text{C} \) (when the outside air temperature is \( T=20 \, ^\circ\text{C} \)). Thereat, the air flow in the wind tunnel duct has to be cooled by \( \Delta T=4.9 \, ^\circ\text{C} \) to which end the needed mass of outside air flow is \( G=1465.5 \, \text{kgs}^{-1} \) (22% of test section mass air flow). At that, the wind tunnel compressor power is \( N=33.1 \, \text{MW} \).

In the second option the inlet neck is also located in the midsection of diffuser 2, the outlet neck – in the midsection of diffuser 3 (after the compressor). The calculation has shown that the mass air flow of \( G=1357.1 \, \text{kgs}^{-1} \) (20% of test section mass air flow) is sufficient for cooling air and to maintain air...
temperature at closed test section inlet at the level of $T=35^\circ$C (when the outside air temperature is $T_f=20^\circ$C). At that, the wind tunnel compressor power is $N=31.1$ MW.

4. Numerical study of air flow in wind tunnel circuit components in presence of holes

Numerical study of air flow in circuit components of the projected subsonic wind tunnel is made based on ANSYS FLUENT Software System. Design conditions are shown in Table 2.

| Table 2. Calculation parameters |
|--------------------------------|
| Design mode | Inlet boundary conditions | Outlet boundary conditions | Inlet boundary conditions | Outlet boundary conditions | Outside air | Wall |
|-------------|---------------------------|-----------------------------|---------------------------|-----------------------------|-------------|------|
| 1           | $T_0, K$ | $p_0, Pa$ | $T_0, K$ | $p, Pa$ | $T_\infty, K$ | $p_\infty, Pa$ | Wind tunnel segment between corners 3 and 4 | 293 | 101325 | $q_w=0$ |
| 2           | 320.7 | 102402 | 316.8 | 99651 | 320.9 | 104710 | 320.7 | 104284 |
| 2           | 320.7 | 102382 | 317.0 | 99686 | 321.0 | 104721 | 320.7 | 104283 |

The first design mode corresponds to the first option of hole locations (in diffuser 2 and at the wind tunnel segment between corners 3 and 4) and to the inlet test section temperature $T=35^\circ$C. The second design mode corresponds to the second option of hole locations (in diffusers 2 and 3) and to the inlet test section temperature $T=35^\circ$C.

Dependence of air viscosity on temperature is defined by Sutherland's law:

$$\mu(T) = 1.716 \cdot 10^{-5} \left( \frac{T}{273.11} \right)^{1.5} \frac{273.11 + 110.56}{T + 110.56}.$$  \hspace{1cm} (5)

Dependence of thermal conductivity $\lambda$ on temperature is defined by the tabular air data [5] approximated with second-degree polynomial

$$\lambda(T) = C_0 + C_1 T + C_2 T^2,$$  \hspace{1cm} (6)

Where $C_0=-2.097 \cdot 10^{-3}$; $C_1=1.117 \cdot 10^{-2}$; $C_2=-5.653 \cdot 10^{-8}$.

The calculation was made on the assumption of developed turbulent flow with the use of S-A and SST turbulence models.

Figures 2-3 show some results of flow calculation in diffuser 2 and at the wind tunnel segment between corners 3 and 4 for the first design mode.

**Figure 2.** Flow rate, static pressure, and static temperature in diffuser 2.
Figure 3. Flow rate, static pressure, and static temperature at the wind tunnel segment between corners 3 and 4.

Notice that a series of calculations is made for different configurations of input and output hole walls.

Calculation analysis of the flow in diffuser 2 has shown that injected flow moves along the walls of diffuser. In the zone near the walls of the diffuser, the velocity is lower than in the core of the flow. Total and static temperature are also lower ($T = 291.1$ K). Static pressure in the wind tunnel duct decreases as the air inflows.

Calculation analysis of the flow at the wind tunnel segment between corners 3 and 4 has shown that if a portion of air flow goes through a hole, the duct flow rate decreases (from 34.1 to 27.8 ms$^{-1}$) while static pressure increases. Static temperature in the duct does not change, whereas total temperature changes insignificantly.

Figure 3 shows that the duct air outflow is rather high (up to $w_{out} = 80-90$ ms$^{-1}$). So it can give rise to unwanted vibrations, therefore a stationary air cooler should be applied for acoustic tests in wind tunnels.

Distribution of main flow parameters in the wind tunnel circuit is shown in Table 3.

| Table 3. Flow parameters (first design mode) |
|---------------------------------------------|
| Wind tunnel segment                         | Input parameters | Output parameters |
|                                             | $T_{in}$ °C | $T$, °C | $w$, ms$^{-1}$ | $T_{in}$ °C | $T$, °C | $w$, ms$^{-1}$ |
| Test section                                | 47.7      | 35.0   | 160.0          | 47.7      | 38.9   | 133.3          |
| Diffuser 1                                  | 47.7      | 38.9   | 133.3          | 47.7      | 45.3   | 69.7           |
| Corner 1                                    | 47.7      | 45.3   | 69.7           | 47.7      | 45.3   | 69.7           |
| Diffuser 2                                  | 43.8      | 40.9   | 77.4           | 43.8      | 41.3   | 70.8           |
| Corner 2                                    | 43.8      | 41.3   | 70.8           | 43.8      | 41.3   | 70.8           |
| Compressor chamber                          | 43.8      | 41.3   | 70.8           | 47.9      | 47.0   | 42.4           |
| Diffuser 3                                  | 47.9      | 47.0   | 42.4           | 47.9      | 47.4   | 34.1           |
| Corner 3                                    | 47.9      | 47.4   | 34.1           | 47.9      | 47.4   | 34.1           |
| Wind tunnel segment                         | 47.9      | 47.4   | 34.1           | 47.9      | 47.4   | 34.1           |
| Corner 4                                    | 47.7      | 47.4   | 27.8           | 47.7      | 47.4   | 27.8           |
| Diffuser 4                                  | 47.7      | 47.4   | 27.8           | 47.7      | 47.6   | 16.2           |
| Stilling chamber                            | 47.7      | 47.6   | 16.2           | 47.7      | 47.6   | 16.2           |
| Nozzle                                     | 47.7      | 47.6   | 16.2           | 47.7      | 35.0   | 160.0          |
Similar results are obtained for the second design mode.

5. Conclusion
The completed study shows that mass air flow of outside air making 20-22% (of airflow rate in the wind tunnel duct) at the temperature $T_f=20$ °C is sufficient to keep static temperature in the test section at the level of $T=35$ °C. At that, the compressor capacity insufficiently increases (to $N=31-33$ MBr). In general, if air exchange with the ambient environment is used, it can reduce costs of wind tunnels construction and maintenance. The results of this study have formed the basis of R&D support for TsAGI new subsonic wind tunnel.

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