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Analysis of the possibility to increase the Mach number in the T-34 hypersonic wind tunnel

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The T-34 hypersonic blowdown intermittent wind tunnel, used for ballistic and gas-thermodynamic model testing, is described in the paper. A pressure-vacuum flow scheme is used in order to achieve hypersonic speeds. The basic technical data and the description of the main wind tunnel parts are given. The nominal Mach number value is M=7 and its increase is considered in this paper.

Key words: **experimental aerodynamics, wind tunnel, hypersonic flow.**

Used symbols:

Re – Reynolds number
M – Mach number
T_t – static temperature in front of the normal shock wave, K
$T=T_1$ – static temperature in front of the normal shock wave, K
T_2 – static temperature behind the normal shock wave, K
t – wind tunnel run duration
$p_1=p$ – static pressure in front of the normal shock wave, bar
p_2 – static pressure behind the normal shock wave, bar
$p_{t1}=p_t$ – total pressure in front of the normal shock wave, bar
p_t – settling chamber total pressure, bar
p_{t2} – total pressure behind the normal shock wave, bar
p_r – vacuum tank pressure, bar
$\rho_1=\rho$ – density in front of the normal shock wave, kg/m^3
ρ_2 – density behind the normal shock wave, kg/m^3
ρ_k – density in the nozzle throat, kg/m^3
ρ_t – density under the conditions of total pressure and temperature, kg/m^3
p – test section static pressure, bar
a_k – speed of sound in the nozzle throat, m/s
a_t – speed of sound, m/s
S – nozzle throat cross section area, m^2
Q_m – nozzle throat mass flow, kg/s
V – vacuum tank volume, m^3
R – gas constant, Nm/K
α – angle of attack, °
Φ – roll angle, °
γ – specific heat ratio for adiabatic process
NUT – normal shock wave

Introduction

THE T-34 hypersonic wind tunnel was designed and manufactured in the period between 1974 and 1984. Nozzle manufacturing was the greatest challenge. The technical requirements for nozzle manufacturing were too high for the VTI workshop at that time. During the previous years one nozzle of good quality was built thus enabling some limited testings. The wind tunnel was designed for a Mach number of 7. All wind tunnel components were built for this designed value of the Mach number. Higher Mach numbers are not possible to achieve with a simple installation of a new nozzle. It is necessary to analyze the technical characteristics of all wind tunnel components. Above all, it is necessary to consider the compressor unit, heater and pressure regulating valve in front of the settling chamber.

The aim of this paper is to consider a possibility of wind tunnel Mach number increasing.

Description and basic wind tunnel characteristics

The wind tunnel is of the intermittent type with over pressure. The pressure-vacuum flow scheme is used in order to achieve hypersonic Mach numbers [1]. The pressure in the air storage tank and the pressure in the vacuum tank provide necessary pressure ratio for hypersonic Mach numbers. The wind tunnel block diagram is given in Fig.1

The basic wind tunnel components are:

1. Air conditioning unit
2. Air storage tank
3. Shut-off valve
4. Air heating system
5. Pressure regulating valve
6. Settling chamber
7. Nozzle
8. Test section
9. Shut-off valve
10. By-pass

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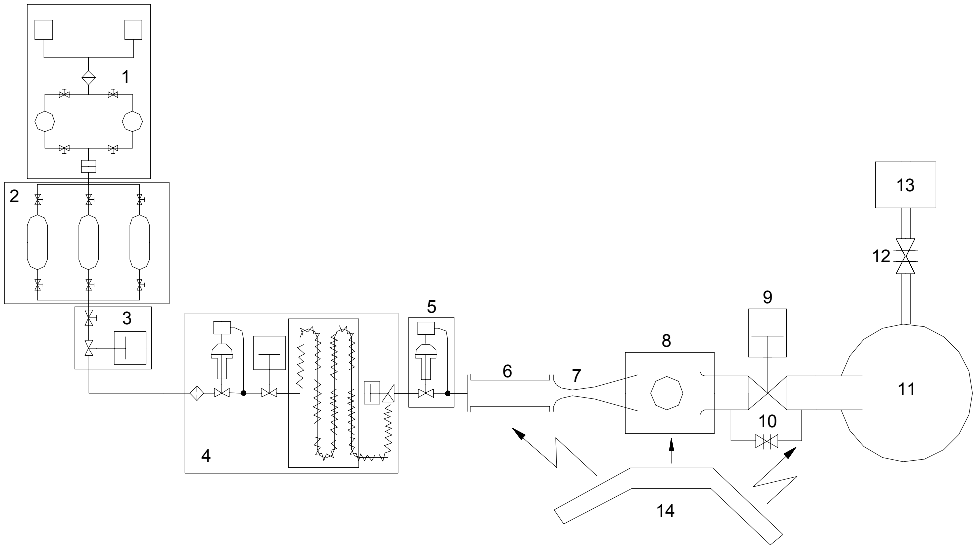

Figure 1. Wind tunnel block diagram

11. Vacuum tank
12. Shut-off valve
13. Vacuum pump
14. Wind tunnel control desk

The wind tunnel test section is situated in a closed chamber together with the rear part of the nozzle, the model support system and the front end of the diffuser.

The air from the nozzle creates a working jet with a diameter of 160 mm or 220 mm and with an area of 0.020 m^2 and 0.038 m^2.

The aerodynamic characteristics are:

- Mach number of 7.0
- Reynolds number of $12.5\text{x}10^6$ m^{-1} at a Mach number of 7.0
- Maximum total pressure of 30 bar at a Mach number of 7.0
- Maximum static pressure of 7.25 mbar at a Mach number of 7.0
- Total temperature of 720 K
- Wind tunnel run duration of 60 s
- Wind tunnel annual capacity is two runs per day.

The maximum values of wind tunnel Reynolds numbers are given in Fig.2. The nominal nozzle diameter value is used for Reynolds number calculations. There are two Reynolds numbers envelopes. The upper limit is achieved for the maximum value of the wind tunnel total pressure while the lower limit is achieved for the minimum value of the wind tunnel total pressure for a given test section Mach number.

The total temperature is defined according to the requirement to avoid liquefaction phenomena in the test section and is given in Fig.3.

The model support system characteristics are:

- Angle of attack range of ±10^0, sweep mode
- Roll angle range of ±360^0, sweep mode
- Maximum normal force 200 N

A wind tunnel model size is limited because of the blockage effects in the wind tunnel test section. A model cross section area is up to 0.005 m^2. The recommended model length is 0.125 m.

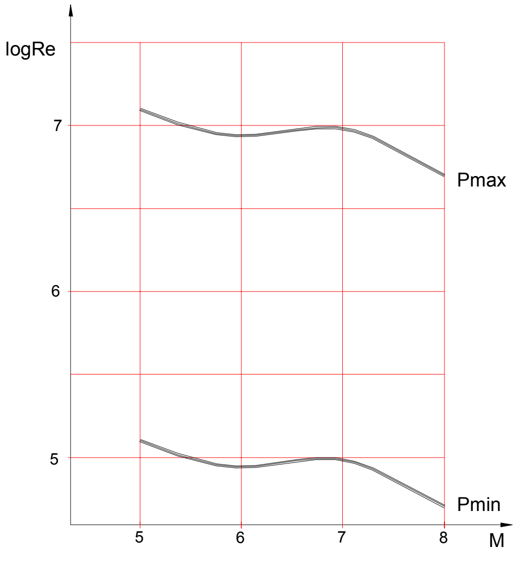

Figure 2. Reynolds number as a function of Mach number in the test section

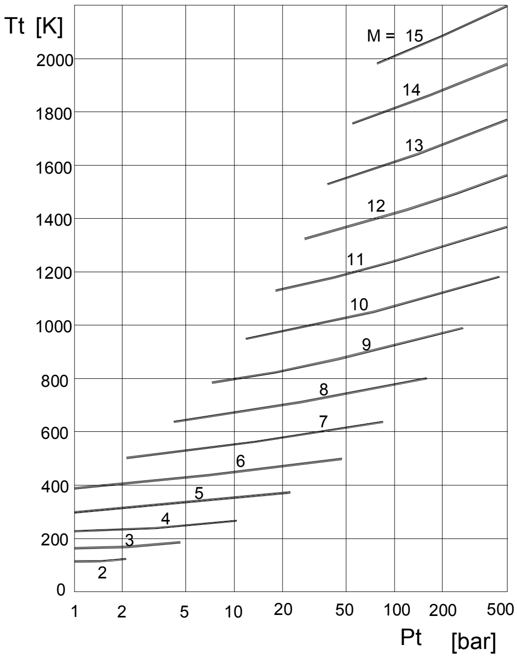

Figure 3. Liquefaction temperature as a function of Mach number and total pressure

Basic wind tunnel gas-dynamic calculations

Determination of the wind tunnel run duration

Run duration is an important parameter which defines total time for experiment [2]. The experiment time is always shorter than the total wind tunnel run duration. The main phases are start up, flow establishing, stationary flow and flow stopping.

The supersonic flow around the model is established only in the case of proper flow parameter ratios. Fig.4 shows the supersonic flow obtaining process in the test chamber. a. - Normal shock wave is in the nozzle; b and c. - - Normal shock wave passes over the model, d. - Oblique shock waves, the normal shock wave is behind the model.

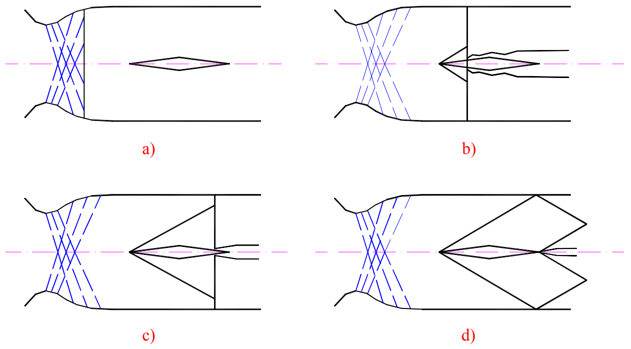
a) b) c) d)

Figure 4. Supersonic flow obtaining process in the test chamber

Knowing that gas-thermodynamic parameters are changing, the flow field shown in Fig.5 is obtained for limit conditions, at the moment when the regular flow disappears. The limit values of gas-thermodynamic parameters of the regular flow starting and stopping are given in Table 1. The regular flow disappears when the normal shock wave is formed at the nozzle exit, as shown in Fig.5.

Table 1.

M	T_t	p/p_t	ρ/ρ_t	p_2/p_1	ρ_2/ρ_1	T_2/T_1	p_{t2}/p_{t1}	p_1/p_{t2}
5	0.1667	0.00189	0.01134	29.0	5.0	5.8	0.06172	0.0362
6	0.1212	0.0006334	0.005194	41.83	5.268	7.94	0.02965	0.02136
7	0.09259	0.0002416	0.002609	57.0	5.444	10.47	0.01535	0.01574
8	0.07248	0.00001024	0.001414	74.50	5,565	13.39	0.008488	0.01207
9	0.05814	0.00004739	0.000815	94.33	5.651	16.69	0.004964	0.009546
10	0.04762	0.00002356	0.0004948	116.5	5.714	20.39	0.003045	0.007739

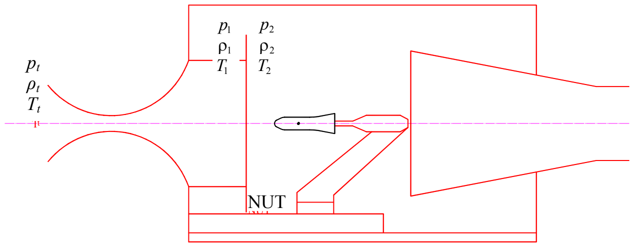

Figure 5. Wind tunnel test section – gas-thermodynamic parameters at the moment when the regular flow disappears

The basic values for the wind tunnel time duration calculation are:

$$p_t = 30 \text{ bar}$$

$$T_t = 720^{\circ}\text{K}$$

$$\rho_t = \frac{p_t}{R \cdot T_t} = 14.518 \ \frac{\text{kg}}{\text{m}^3}$$

$$a_t = \sqrt{\gamma \cdot R \cdot T_t} = 537 \frac{\text{m}}{\text{s}}$$

$$\frac{\rho_k \cdot a_k}{\rho_t \cdot a_t} = 0.579$$

D=0.0138 m throat diameter
S=0.0001495 m^2 nozzle throat cross section area

Air mass flow:

$$Qm = \rho_t \cdot a_t \cdot \frac{\rho_k \cdot a_k}{\rho_t \cdot a_t} \cdot S = 0.67 \frac{\text{kg}}{\text{s}}$$

Run time duration in accordance to [1], [5] and [6]:

$$t = \frac{\rho_t}{\gamma \cdot Q_m} \cdot V \cdot \left(0.6 \cdot \frac{p_{t2}}{p_{t1}} - \frac{p_r}{p_t} \right) = 61.2 \text{ s}$$

$$p_r = 0.020 \text{ bar}$$

$$V = 485 \text{ m}^3$$

$$\frac{p_{t2}}{p_{t1}} = 0.01535$$

Mach number increasing possibility

Ratios of total (T_t,p_t,ρ_t) and static values (T,p,ρ), static values through the normal shock wave (T_1,p_1,ρ_1 and T_2,p_2,ρ_2), total values through the normal shock wave (T_{t1},p_{t1},ρ_{t1} and T_{t2},p_{t2},ρ_{t2}), temperature, pressure and density for the Mach number range from 5 to 10 were taken from the tables in [3]. The calculated values of these ratios are given in Table 1.

The wind tunnel test section static pressure has been calculated using the parameters from Table 1 and the following equation:

$$p = p_t (1 + \frac{\gamma - 1}{2} M^2)^{\frac{-\gamma}{\gamma - 1}}$$

for the Mach number range from 5 to 10 and the total pressure values of 30, 60 and 90 bars. The calculated static pressure values are given in Table 2.

Table 2.

M	5	6	7	8	9	10
p_t	30	30	30	30	30	30
p	**0.0567**	**0.0190**	**0.007248**	0.003077	0.00142	0.0007
p_t	60	60	60	60	60	60
p	0.1134	0.038	0.014496	0.006144	0.00284	0.0014
p_t	90	90	90	90	90	90
p	0.1701	0.057	0.021744	**0.009216**	0.00426	0.0021

The minimum pressure in the vacuum tank is 0.007 bars. From Table 2 it is obvious that the existing installation can achieve Mach numbers 5, 6 and 7.

A Mach number of 8 can be achieved with a new pressure regulating valve and with a pressure of 90 bars.

In the existing installation, the pressure decrease behind the tank is from 200 bars to 90 bars. Under this pressure, air temperature is 720 K and the air is directed to the entrance of the pressure regulating valve.

A Mach number of 8 can be achieved at a temperature of 720K without the appearance of liquefaction phenomena. This is obvious from Fig.3.

Basic characteristics of the wind tunnel components as a function of Mach number increase

The basic components of the T-34 wind tunnel are:

Air conditioning unit

The air conditioning unit consists of two compressors, the oil extractor and the air dryer. Each of two four-stage piston compressors Bauer (Fig.6) has a working pressure of 200 bars and a capacity of 0.9 m^3/h. The air dryer type is Duplex-10L. Air humidity behind the air dryer is 0.1 g water per kilo of dry air.

Figure 6. Bauer compressors

Air storage tanks

There are three air storage tanks (Fig.7). Each tank volume is 3.3 m^3 and the total volume is 10.0 m^3. The maximum pressure in the air storage tanks is 200 bars.

Figure 7. Air storage tanks

Air heater

The air heater consists of a spiral pipe with the air flowing under pressure (Fig.8). Around the pipe there are 12 heater sections. The total power for each heater section is 3 kW. The air temperature is up to 500^0C. This is a requested temperature to avoid liquefaction phenomena, i.e. the decrease of air temperature because of the air expansion in the test chamber working at a required Mach number.

Figure 8. Air heater

For Mach number increasing it is necessary to change the air heating unit. The existing installation has not enough thermal capacity for Mach numbers higher than a Mach number of 8.

Wind tunnel tube

The wind tunnel tube (Fig.9) consists of the pressure regulating valve, the settling chamber and the nozzle. The main task of the pressure regulating valve is keeping a constant blowing pressure during the run, with the range from 30 to 60 bars. The required blowing pressure depends on a Mach number value and the run duration. The settling chamber has a shape of a hollow cylinder with copper inserts. The copper inserts are elements for improving flow quality at the entrance of the nozzle. The nozzle is symmetrical, with fixed geometry. The T-34 wind tunnel has a nozzle for a Mach number of 7.

For Mach number increasing it is necessary to change the pressure regulating valve and design a nozzle for higher Mach numbers.

Figure 9. T-34 wind tunnel tube

Test section

The test section is in a closed chamber which can withstand pressure over 200 bars. The chamber walls have Shieleren windows. The model support system is inside the chamber (Fig.10). Besides putting a model in the desired position during the run, there is another function typical for hypersonic wind tunnels. After start up and flow establishing, the model support system puts a model in the working jet. This function has a great importance for the model safety.

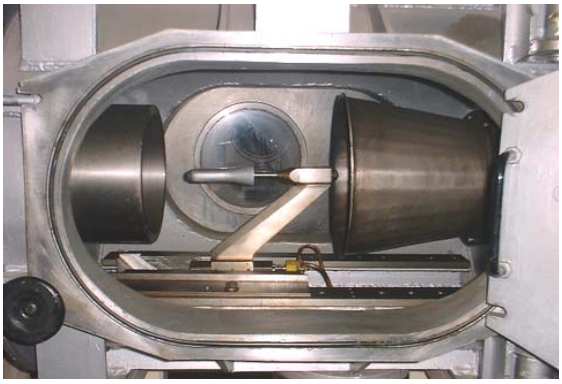

Figure 10. Wind tunnel test section

Vacuum tanks

There are two connected tanks (Fig.11). The volume of the first one is 820 m^3 and the volume of the second one is 485 m^3. The total volume is 1305 m^3. Only the 485 m^3 tank is used for the T-34 wind tunnel.

Figure 11. Vacuum tanks

Vacuum pump

The vacuum pump of the French firm MPR is used in the T-34 hypersonic wind tunnel (Fig.12). The vacuum pump can reach pressure up to 0.006 bars. For a volume of 485 m^3, that pressure can be reached in one hour.

Figure 12. MPR vacuum pump

Conclusion

The T-34 hypersonic wind tunnel is used for studying gas and thermodynamic phenomena. Special equipment is required due to the complexity of flow phenomena in the wind tunnel test section. Heating problems are main characteristics of this wind tunnel type. In spite of these facts, due to very short duration of test, measuring equipment such as strain gage balances, pressure scanners and other classical equipment are commonly used. An assumption is introduced that there is no significant influence of heating on the measuring process with the run duration up to 3 s.

The original systems in the wind tunnel were designed for a Mach number of 7.

Mach number increasing is limited because of the originally assembled equipment. There is a possibility for achieving a Mach number of 8, but it is necessary to replace the pressure regulating valve and design and manufacture a new nozzle for M=8. Besides the performances of the pressure regulating valve and the nozzle, attaining Mach numbers higher than 8 is also limited by the heating unit power.

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Analiza mogućnosti povećanja Mahovog broja hipersoničnog aerotunela T-34

Dat je opis hipersoničnog aerotunela T-34 VTI. Aerotunel je prekidnog dejstva sa nadpritiskom, realizovan je u šemi strujanja nadpritisak − vakuum, koja omogućuje postizanje hipersoničnih Mahovih brojeva. Date su osnovne karakteristike aerotunela i opis glavnih komponenti aerotunela. Aerotunel se koristi za balistička i gaso-termodinamička ispitivanja na odgovarajućim modelima. Nominalni Mahov broj za aerotunel T-34 je M=7 a u radu se razmatraju mogućnosti postizanja većih Mahovih brojeva.

Ključne reči: **eksperimentalna aerodinamika, aerotunel, hipersonično strujanje.**

Analyse de la possibilité d'augmenter le nombre de Mach de la soufflerie hypersonique T-34

Les caractéristiques et les éléments principaux de la soufflerie hypersonique à rafales T-34 sont donnés. La soufflerie, réalisée selon le principe „surpression − vacuum", est utilisée pour les essais balistiques et les essais de la thermodynamique de gaz effectués sur des maquettes. Le nombre nominal de Mach est de l'ordre de 7 et cet article prend en considération la possibilité de l'augmenter.

Mots-clés: **aérodynamique expérimentale, soufflerie, écoulement hypersonique.**