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CRYOGENIC TEST RIG WITH AN AERODYNAMIC MAGNETICALLY LEVITATED CARRIAGE

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ABSTRACT

The results of the investigations carried out by the authors in TsAGI in 1983 - 1984 concerning the use of a magnetically levitated aerodynamic carriage with a model moving in a closed cryogenic channel are presented. The facility dimensions are established, operating ranges are calculated, thermal isolation, cooling and measurement systems are described, comparison of this facility with wind tunnels is given and its advantages are shown.

Figures for this paper were unavailable at time of publication.

SYMBOLS

Names

A	area, m^2
V	speed, m/sec
T	temperature, K
L	linear dimension, m
p	pressure, atm
ρ	density, kg/m^3
m	mass, kg or t
q	dynamic pressure, $kg/m\ sec^2$
g	acceleration due to gravity, m/sec^2
t	time, sec
n	load factor
M	Mach number
Re	Reynolds number
St	Strouhal number
Fr	Froude number
Eu	Euler number
R	thrust, t
A	work, MJ
Q	heat, MJ
C_x	drag aerodynamic coefficient
η	engine efficiency factor
C	specific heat of structural material, kJ/kg K
Cp	specific heat at constant pressure, kJ/kg K
Cv	specific heat at constant volume, kJ/kg K
γ	ratio of specific heats, γ = Cp/Cv
β	specific cooling capacity of liquid nitrogen, kJ/kg

Subscripts

$\bar{c}$	reference chord, $0.1\sqrt{A_{TS}}$
c	carriage
LN_2	liquid nitrogen
i	initial
f	final
m	model
TS	test section
s	sum value
a	air
1	conditions at acceleration and at T = 82 K
2	conditions at uniform motion and at T = 290 K
3	conditions at deceleration

INTRODUCTION

In the 1970's a conception of increasing wind tunnel Reynolds number for model tests by decreasing gas temperature was developed which underlay the construction of cryogenic wind tunnels [1 - 5]. The idea of the adaptation of the known aerodynamic carriage method to cryogenic temperature of working medium was considered by the authors in 1983 - 1984 [6,7]. The application of a magnetically levitated aerodynamic carriage with a model attached to it was proposed. This principle of motion had been already used in those years in monorail passenger transport facilities in a number of countries, e.g., in Japan. A few other new facility elements were also proposed: flexible screen simulating the ground surface, sluices etc. A paper of P.L. Lawing and W.G. Johnson [8] was published in 1988, which also proposed using the principle of accelerating the model up to hypersonic speeds being held in the center of a special channel using a Magnetic Suspension and Balance Systems (MSBS) [8,9].

The test rig proposed by the authors is intended mainly for model tests in a subsonic speed range so that the tests would be confined to an acceptable channel length. The importance of an accurate simulation in case of testing models with low subsonic flow speeds increases steadily, special requirements of a small working medium turbulence being specified. Essentially atmospheric turbulence is provided in this facility, and acoustic disturbances can also be eliminated almost fully. The facility is featured by a number of other advantages as compared to operating wind tunnels and test rigs with aerodynamic carriages: smaller model dimensions, almost twice the reduction in motion speed as compared to tests at normal temperatures, ground effect simulation at take-off and landing, and investment and energy savings. A very important feature of magnetically levitated transport facilities is their ecological friendliness.

Experimental results for high-temperature superconductivity (at temperatures $\leq$ 100 K) were obtained in 1985 - 1987. The industrial application of high-temperature superconductivity in the magnetically levitating transport drive systems can contribute to a considerable energy consumption reduction.

In recent years, the interest in the use of heavy gases in wind tunnels to increase the Reynolds number has grown. This concept can be used in the proposed test rig. The value of ratio of specific heats γ for heave gases that can differ from the value of γ for air is not so significant at small subsonic speeds.

PRINCIPLE OF SIMULATION IN A CRYOGENIC CHANNEL

The theoretical validation of the possibility of using cryogenic flow temperatures in wind tunnels is given in references [2,3]. We shall assume that the flow temperature in conventional low-speed wind tunnels is $T_1 = 300$ K, and the air temperature in the cryogenic test rig channel is equal to the air condensation temperature $T_2 = 82$ K and the pressure is atmospheric. Using the known relations for the speed $V \propto T^{0.5}$ and the Reynolds number $Re \propto T^{-1.36}$, we obtain:

$$V_2/V_1 = (T_2/T_1)^{0.5} = 0.523$$

$$Re_2/Re_1 = (T_1/T_2)^{1.36} = 5.84$$

If the full-scale value of the Reynolds number is reproduced, the model size can be reduced in accordance with the relation $L \propto T^{1.36}$. In this case, for the Strouhal number St and Froude number Fr we shall have:

$$St_2/St_1 = (T_1/T_2)^{0.86} = 0.328$$

$$Fr_2/Fr_1 = (T_1/T_2)^{-0.36} = 1.60$$

The Euler number $Eu = p/\rho V^2$ does not depend on temperature. This means that it is possible to reproduce full-scale values of Mach, Reynolds and Euler numbers and the values of Strouhal and Froude numbers that are close to full-scale ones.

DETERMINATION OF FACILITY DIMENSIONS

As a standard operation regime we shall consider tests carried on according to the following program: uniform model acceleration, motion at a constant speed and uniform deceleration. The tunnel length is found as a sum of three lengths of acceleration (L_1), uniform motion (L_2), and deceleration (L_3) sections. The uniform motion time is assumed to be equal to 1 sec. Table 1 gives the motion times for first and third sections and the lengths of all sections L_s in case of uniform model acceleration and deceleration with load factor n for different maximum Mach numbers.

An essential part of the channel is occupied by acceleration and deceleration sections, their lengths being dependent on load factor values. It is difficult to attain supersonic Mach numbers in the tunnel even at considerable load factors n = 5 to 10 because of a great channel length (up to 7 km) and increased model strengths required. To obtain high, sub, and transonic Mach numbers at moderate load factors (up to n = 4) the required channel length will be approximately 1 km (fig. 1). The most simple solution would be the construction of a channel for take-off and landing speeds. Thus, at n = 4 for the Mach number M = 0.2, the total channel length amounts to L_s = 70 m, and for M = 0.45, L_s = 252 m. The total channel length should be extended slightly so that safety measures could be provided during model deceleration. Chambers of the diameter of approximately 10 m should be provided at both channel ends for model rotations. These chambers must communicate with sluices for model heating and cooling.

We shall assume such channel cross section area that the Reynolds number

Re_c would have the same value as in the largest operating low-speed wind tunnel at the Ames Research Center, NASA, USA [10]. With the test section of this wind tunnel A_{TS} = 36 × 24 m and maximum speed V = 50 m/s, the Reynolds number Re_c ≈ 10 mil. The same Reynolds number is achieved in the proposed cryogenic test rig at T=82 K with cross section area 6.2 × 4.1 m. For further calculations we shall assume the following main facility parameters: M = 0.45, n = 4 (for acceleration and deceleration), L = 290 m, A = 6.2 × 4.1 m. Figure 2 presents a sketch of the cryogenic channel.

OPERATING RANGES

An air-nitrogen mixture is used as a working medium. The oxygen-nitrogen ratio in the mixture can be arbitrary, since judging by investigation results, presented in [3], the tests in air and nitrogen are essentially identical. The minimum value of the working gas temperature is equal to the air condensation temperature T = 82 K. The maximum gas temperature in the channel is equal to the ambient temperature T = 290 K.

Figure 3 shows an operating range of the facility in coordinates of M and Re numbers for a selected channel length L = 290 m. This range is confined by lines, that correspond to maximum and minimum temperatures and maximum Mach number. At temperature T ≤ 121 K, the model can be accelerated up to M = 0.45, and at T = 121 K the choice should be confined to the values of the Mach number M < 0,45. Figures 4 and 5 present uniform motion time t_2 and model speed V versus Mach number. The maximum model velocity that can be attained at n = 4 is equal to V = 99 m/s. At T = 82 K and M = 0.45, the speed V = 82 m/sec

THERMAL ISOLATION, COOLING AND COLD PRESERVATION IN FACILITY

To attain and keep a low temperature of the working medium, the supply of liquid nitrogen is provided which, being evaporated, cools the channel gas. Liquid nitrogen will be supplied to special evaporators distributed uniformly along the channel length. Both the internal and external thermal isolations of the facility can be made of foam plastics. Among various types of the thermal isolation of the cryogenic channel, the application of screen-vacuum or vacuum-powder isolation providing the heat flux about 1 W/m^2 seems to be promising.

We shall evaluate the amount of liquid nitrogen required for initial cooling of the facility. With above chosen dimensions the total facility surface area will be A = 6550 m^2. The steel casing mass m ≈ 200 t. The quantity of liquid nitrogen m_{LN_2} is calculated from the heat balance equation (assuming mean values of specific heat of steel C and specific cooling capacity of liquid nitrogen β for the temperature range 82 to 290 K):

$$m_{LN_2} = \frac{mC(T_i - T_f)}{\beta} \approx 50 \text{ t}$$

The total facility volume (channel and chambers) is 8000 m^2, air mass at room temperature m_a = 9600 kg. The following quantity liquid nitrogen is required for its cooling:

$$m_{LN_2} = \frac{m_a\, C_p\, (T_i - T_f)}{\beta} \approx 10\ t$$

The total quantity of the liquid nitrogen for initial cooling of the channel casing and air inside it is equal approximately to 60 t.The mass of the aerodynamic carriage with a model is evaluated to be about 5 t. After an initial model installation or its reinstallation approximately 2 tons of liquid nitrogen are required for cooling. Heat losses due to thermal isolation in case of screen-vacuum isolation cannot be taken into account.

CHOICE OF TRANSPORT DEVICE

One of the main problems in the development of the facility under discussion is the choice and designing of the aerodynamic carriage. In a cryogenic temperature channel it is reasonable to apply a monorail levitating carriage with a linear electric engine. According to information of the late 1970's a high-speed test route with such a transport system had been designed in West Germany for the operation in the open atmosphere, so that to simplify the carriage maneuvers in chambers and sluices it is mounted on an ordinary rail track (fig.2).

The thrust acting on the carriage is equal to:

in the acceleration

$$R_1 = mng + (C_{x,m}\ A_m + C_{x,c}\ A_c)q$$

in the uniform motion

$$R_2 = (C_{x,m}\ A_m + C_{x,c}\ A_c)q$$

in the deceleration

$$R_3 = -(mng - (C_{x,m}\ A_m + C_{x,c}\ A_c)q)$$

where A_m, A_c - the characteristic aerodynamic model and carriage areas.

We think that the carriage is decelerated by means of an electric brake giving up the energy to the network. Assume the following values: $C_{x,m} = 0.5$; $C_{x,c} = 0.1$; $A_m = 2.5\ m^2$; $A_c = 3.0\ m^2$. A maximum thrust is required by the end of the model acceleration, e.g., at M = 0.45 we obtain P = 21.8 t.

Figure 6 shows the dependence of the driver power $N=RV/\eta$ (where $\eta = 0.95$) on time for three characteristic ranges: 1) M = 0.45, T = 121 K (maximum power); 2) M =0.45, T =82 K; 3) M= 0.2, T = 82 K. The maximum required power is 23 MW.

We shall find the heat transfered to the channel. The work done in one model run is equal to:

$$A = \int_0^{ts} (R_1 + R_2 + R_3)dt = (C_{x,m}\ S_m + C_{x,c}\ S_c)\int_0^{ts} \frac{\rho V^3}{2} dt$$

where $t_s = t_1 + t_2 + t_3$, $V_1 = ngt$, $V_3 = (V_2 - ngt)$. Accounting for the relations $t_1 = t_3$ and $V_2 = ngt_1$ we obtain:

$$A = (C_{x,m} S_m + C_{x,c} S_c) \frac{\rho V_2^3}{2} \left(\frac{t_1}{2} + t_2 \right)$$

We also consider that $(1 - \eta)100\% = 5\%$ of current work in the network independent of its direction converts to heat. This heat is equal to:

$$Q = (1 - \eta) \int_0^{t_s} (R_1 + R_2 + R_3)dt = (1 - \eta) \left[mV_2^2 + (C_{x,m} S_m + C_{x,c} S_c) \frac{\rho V_2^3}{2} t_2 \right]$$

For the conditions $M = 0.45$ and $T = 82$ K we have: $A = 3.7$ MJ, $Q = 1.8$ MJ. To compensate this heat, the following liquid nitrogen is required:

$$m_{LN_2} = \frac{(A + Q)}{\beta} = 27 \text{ Kg}$$

For the regime $M = 0.2$ and $T = 82$ K we have $m_{LN_2} = 7$ kg. The consumption amount of liquid nitrogen will be less or, at least, commensurable with specific consumption per second of a run in a cryogenic compressor tunnel with test section 6.2 x 4.1 m and the same Mach and Reynolds number.

MEASUREMENT SYSTEM

The following important specific requirements are applied to the data measurement, recording and processing system in case of aerodynamic and strength model tests:

1. All instrumentation devices must be mounted on the aerodynamic carriage.

2. The serviceability of all devices must be provided at temperatures 82 - 300 K and load factor $n = 4$.

3. The speed of data measuring, recording and processing systems must correspond to the experiment time.

4. The measurement accuracy must be no less then that of existing low-speed wind tunnels.

The measuring devices applied in cryogenic and shock wind tunnels can be used for the most part in this facility, too.

FACILITY FEATURES

The absence of working medium disturbances in front of the model makes it possible to make the facility low-turbulent. Of importance is the absence of a complex labor-consuming tunnel element of the facility, namely: a compressor. At the same time the manufacturing of special supports and models capable of withstanding the load factor of n = 4 at the temperature T = 82 K will be required.

Note a number of new kinds of unique tests that can be conducted in this facility:

1. The model acceleration and deceleration according to a specified time program simulating aircraft take-off and landing V = V(t,H) by changing the shape of a special flexible screen simultaneously with varying model angle of attack.

2. The determination of the Reynolds number influence on aerodynamic model characteristics by varying the medium temperature.

3. The formation, in a certain tunnel section, of jet gas flows simulating side gusts.

OPERATION ORGANIZATION. COMPARISON WITH WIND TUNNELS

The following operation mode of the facility is assumed. Cooling is undertaken one time a month with its subsequent continuous operation. In order to speed up to model reinstallation it is possible to apply two carriages and to mount one model and test the other one simultaneously. When heating it is possible to carry on tests in the temperature range of T = 82 K to 290 K. Model and carriage heating and cooling can be carried on in two special small-volume sluices: in a warm one for heating up and in a cold one for cooling down. The excessive gaseous nitrogen is ejected into the atmosphere through a 50 m-high exhaust tube.

Table 2 presents the main characteristics of the cryogenic channel in comparison with the TsAGI T-101 wind tunnel and the wind tunnel with the test section area 36 × 24 m (Ames RC, NASA, USA).

CONCLUSIONS

1. The aerodynamic test rig with channel cross section 6.2 × 4.1 m and with the length of 290 m provides the possibility of model testing at the Reynolds number $Re_{\bar{c}} = 31 \cdot 10^6$ in the Mach number range M = 0.45. The steady-state model motion time is 1 sec.

2. The required maximum power of the aerodynamic carriage engine is N ≈ 23 MW. The consumption of liquid nitrogen for test rig cooling is about 60 t. For one model run at M = 0.45, 27 kg of liquid nitrogen is required, the consumption amount at M = 0.2 is 7 kg.

3. The advantages of this facility are

the possibility of attaining those Re, M, Eu, Fr and St numbers at small subsonic speeds (M < 0.45) which are close to full-scale ones;

model size reduction as compared to those tested in existing conventional wind tunnels while simulating the same Reynolds numbers;

low medium turbulence;

increasing experimental possibilities as compared to wind tunnels;

the possibility of performing new types of tests: acceleration and deceleration, imitation of the runway effect;

reduction in required power and liquid nitrogen consumption as compared to a cryogenic wind tunnel having the same dimensions and parameters;

ecological friendliness of the facility.

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TABLE 1. LENGTH OF THE CHANNEL SECTION AND TIME OF THE CARRIAGE ACCELERATION AND DECELERATION

Mach number	Time t, sec; length L, m	Load factor n					
		1	2	3	4	5	10
0.2	t1 = t3 L1 = L3 L2 Ls	3.7 67 36 170	1.9 34 36 104	1.2 22 36 80	0.93 17 36 70	0.74 13 36 63	0.37 6.7 36 49
0.3	t1 = t3 L1 = L3 L2 Ls	5.6 151 54 356	2. 8 76 54 206	1.9 50 54 154	1.4 38 54 130	1.1 30 54 114	0.56 15 54 84
0.45	t1 = t3 L1 = L3 L2 Ls	8.3 340 82 762	4.2 170 82 422	2.8 113 82 308	2.1 85 82 252	1.7 68 82 218	0.8 34 82 150
1.0	t1 = t3 L1 = L3 L2 Ls	18.6 1690 182 3560	9.3 845 182 1870	6.2 563 182 1310	4.6 423 182 1030	3.7 338 182 860	1.9 169 182 520
3.0	t1 = t3 L1 = L3 L2 Ls	56 15120 544 30790	28 7560 544 15680	19 5070 544 10630	14 3780 544 8110	11 3030 544 6530	5.6 1510 544 3570

TABLE 2. COMPARISON OF MAIN CHARACTERISTICS OF THE FACILITIES

Facility parameters	Cryogenic channel	Tunnel T - 101 TsAGI	USA wind tunnel A = 36 x 24 m
Test section area, m	6.2 x 4.1	14 x 24	36 x 24
Facility dimensions, m	310 x 22	175 x 92	420 x 130
Pressure, atm	1	1	1
Temperature, K	82 - 300	300	300
Much number; speed, m/sec	0.45	up to 60	up to 50
Re numbers, mil	up to 30	6	10
Drive power, MW	23	27	100

Session 10

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