THERMAL EFFECTS INFLUENCING MEASUREMENTS IN A SUPERSONIC BLOWDOWN WIND TUNNEL

by

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During a supersonic run of a blowdown wind tunnel, temperature of air in the test section drops which can affect planned measurements. Adverse thermal effects include variations of the Mach and Reynolds numbers, variation of airspeed, condensation of moisture on the model, change of characteristics of the instrumentation in the model, etc. Available data on thermal effects on instrumentation are pertaining primarily to long-run-duration wind tunnel facilities. In order to characterize such influences on instrumentation in the models, in short-run-duration blowdown wind tunnels, temperature measurements were made in the wing-panel-balance and main-balance spaces of two wind tunnel models tested in the T-38 wind tunnel. The measurements showed that model-interior temperature in a run increased at the beginning of the run, followed by a slower drop, and at the end of the run, by a large temperature drop. Panel-force balance was affected much more than the main balance. Ways of reducing the unwelcome thermal effects by instrumentation design and test planning are discussed.

Key words: *blowdown wind tunnel, thermal matrix, supersonic testing, isentropic flow, thermo-compensation*

Introduction

Blowdown wind tunnels [1, 2] use the energy of air stored in high-pressure tanks. During a wind tunnel *run*, this air is let to flow through the settling chamber, the nozzle and the test section and then discharged into the atmosphere through the diffuser, fig. 1. While the pressure in the storage tank drops, the pressure in the test section is kept constant by means of a regulating valve.

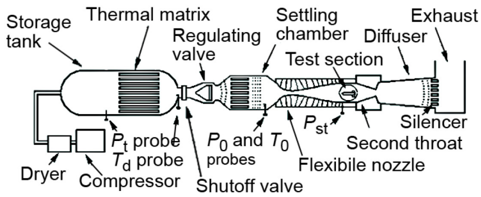

Figure 1. Scheme of a typical blowdown wind tunnel

A characteristic of this type of wind tunnel is that, during a run, the temperature of the working medium drops [1-3] because of its rapid expansion, which can influence measurements to be performed on the test object (model) in the test section. Although provisions are made [4-7] in order to minimize the change of temperature during a test and to minimize its effects on the instrumentation [8-11], it remains an important factor. Adverse thermal effects include variations of the Mach and Reynolds numbers, variation of airspeed during a run at a constant Mach number, and the condensation of moisture from the

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ambient air on the model after a run. Also, mechanical properties of materials used in the production of models and instrumentation can deteriorate at the reduced temperatures [11-13]. Most affected, however, seems to be the instrumentation located in the model, in particular the panel-force balances [14], being close to the model surfaces and most exposed to temperature variations of the air flow.

This problem was brought to attention in the Military Technical Institute (VTI) in Belgrade when temperature variations caused larger-than-expected effects on the fin-panel and wing-panel balances of a supersonic wind tunnel model in the 1.5×1.5 m T-38 trisonic blowdown wind tunnel [15], fig. 2. Although there is considerable data on wind tunnel testing techniques at reduced temperatures [11-13], and effects of temperature changes in general [9, 10] they are relevant mostly to continuous-running facilities and no data related to short-run-duration blowdown wind tunnels could be found that could be of help to resolve the problem. Therefore, in order to obtain an insight on the actual character and magnitude of temperature effects in a particular blowdown wind tunnel environment, temperature measurements were made in the wing-panel-balance space and the main-balance space of two wind tunnel models. Some of the results, showing the observed complex character of the temperature variations, their effects on the instrumentation in the models, and the methods of reducing the unwelcome effects are presented in the paper.

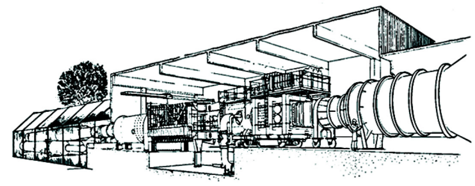

Figure 2. The T-38 trisonic blowdown wind tunnel in the VTI

Temperature variation in a blowdown wind tunnel

One of the main drawbacks of a blowdown wind is the change in temperature of the air leaving the storage tanks and flowing through the wind tunnel tube. This temperature change occurs through three main mechanisms [1, 2]:

- expansion of the air in the emptying air-storage tanks,
- Joule-Thomson process in the pressure-regulating valve, and
- adiabatic expansion of the air through the convergent-divergent supersonic nozzle.

Expansion of air in the tanks

Expansion of the air in the air-storage tanks occurs in each wind tunnel run. Tanks are slowly charged to a relatively-high pressure by a compressor. The air is then rapidly exhausted from the tanks, through a pressure regulating valve, into the wind tunnel tube and the test section, thereafter being discarded through a diffuser into the atmosphere. Such wind tunnel *run* typically lasts from 10 to 40 seconds. The pressure regulating valve maintains a constant stagnation pressure of the flow through the wind tunnel, but the pressure of the air remaining in the tank drops as the air is used, causing a drop of temperature. The process is polytropic because some heat is transferred from the walls of the tank to the air [1], therefore the ratio T_i/T_f of the initial to final temperature is related to the ratio P_i/P_f of the initial to final pressure:

$$\frac{T_i}{T_f} = \left(\frac{P_i}{P_f}\right)^{\frac{n-1}{n}} \tag{1}$$

where n depends on the design of the tanks, ranging from $n = \kappa = 1.4$ (adiabatic) for a configuration with negligible heat transfer to $n = 1$ for an isothermal process. The drop of stagnation temperature can be countered by heaters at the exit end of the tanks, but a much better solution is to use a passive *thermal matrix* capacity-type heater/heat-exchanger.

The theory of operation of thermal-matrix heat-exchangers in wind tunnels was well developed [2-5, 7] in the mid-20th century, when a number of blowdown wind tunnels was designed and built over the world. A typical thermal matrix consists of a large quantity of high-thermal-capacity material placed in the tank in the form that has a high surface-to-volume ratio, empty tin cans piled in the air tanks being one of the cheap and functional design solutions [4]. Heat is transferred to the air as it passes over the matrix, reducing the drops of temperature and tank pressure. The lost heat in the matrix material is recovered automatically during the charging process between the tunnels runs by a transfer from the hot air delivered by the compressor.

When the air-storage tanks are cylindrical in shape, an optimum design of a thermal matrix comprises a large number of thin-walled metal tubes placed parallel to the tank longitudinal axis near the air exit. Tubes are simply packed in the vessels one over another, fig. 3. Convenient tube diameter is about 20 mm, and the length depends on the air mass flow and permitted temperature drop [5], fig. 4 [6].

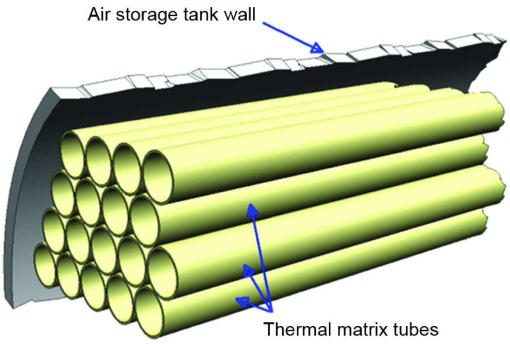

Figure 3. Arrangement of a tubular thermal matrix in a cylindrical air-storage tank of a wind tunnel

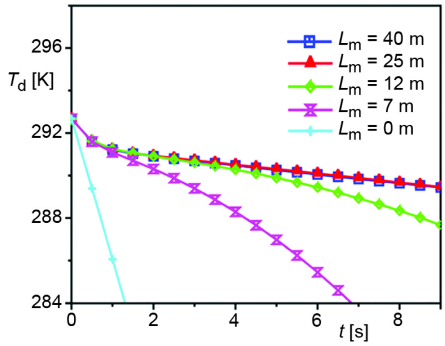

Figure 4. Variation of air-tanks outlet air temperature T_d *vs.* hypothetical lengths, L_m, of thermal matrix in the T-38 wind tunnel

The tubular type of thermal matrix was installed in the air-storage tanks of the T-38 wind tunnel of the VTI. The air-tanks system of this wind tunnel consists of five interconnected cylindrical vessels (fig. 5) with a total volume of about 2600 m^3. The matrix consists of about 70000 7 m-long galvanized-steel pipes with the diameter of 19 mm and with 0.7 mm wall thickness. The pipes are packed in two of the five interconnected air-storage tanks. Total mass of the matrix is about 151000 kg. The matrix was designed so as to limit the air-temperature drop to 7 K during a 6 seconds maximum-flow-rate run at wind tunnel design point (3600 kg/s at M = 1, $P_0 = 600$ kPa), [6]. Measurements performed during the commissioning of the wind tunnel by placing thermocouple probes downstream of the thermal matrix confirmed the functionality of the device, the measured temperature drop being very close to the theoretically-predicted one, fig. 6 [6].

Joule-Thomson process in the regulating valve

When the air from the storage tanks is throttled-down through the pressure-regulating valve of a blowdown wind tunnel, a drop of temperature, referred to as the Joule-Thom-

Figure 5. The system of five interconnected air-storage tanks of the T-38 wind tunnel; tank diameter is 3.8 m

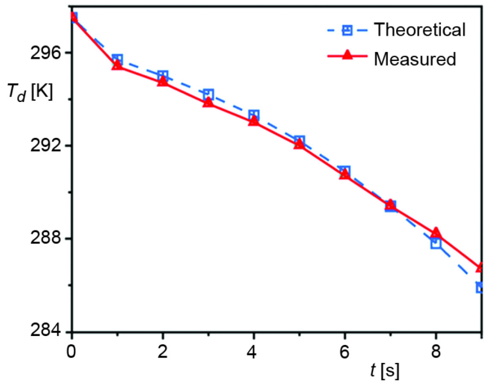

Figure 6. Temperature drop downstream of the thermal matrix in the T-38; M =1.5, P_0 = 680 kPa, mass flow 3050 kg/s

son effect, occurs. In the wind tunnel installations where the ratio of tank pressure to settling-chamber stagnation pressure is high, this real-gas effect can be significant [2, 7]. However, in larger blowdown wind tunnel installations, where the ratio of tank pressure to settling-chamber pressure is relatively low, the effect is minor in comparison to the magnitude of the temperature drop in the storage tanks themselves. Besides, as the pressure in the tanks drops during a wind tunnel run, the Joule-Thomson cooling decreases, thus counteracting the drop of temperature in the tanks.

Isentropic expansion in the supersonic nozzle

Supersonic flow in the test section of a wind tunnel is achieved by the expansion of air through a convergent-divergent nozzle. This flow is governed by the well-known isentropic-flow equations [1]. As the velocity of air in the settling chamber upstream of the nozzle is typically very low (M < 0.05) it is assumed that the air flowing through the nozzle expands from rest and that the conditions in the settling chamber are the stagnation ones. Equation (2), giving the relation of the static temperature, T, to the stagnation temperature T_0, is of interest:

$$T = T_0 \left(1 + \frac{\kappa - 1}{2} \mathrm{M}^2 \right)^{-1} \tag{2}$$

where κ is the ratio of the specific heats (for air, κ = 1.4). Assuming a typical initial stagnation temperature of about 300 K (27 °C), the equation gives the values for the static temperature of air at the entrance to the wind tunnel test section of 207 K (–66 °C) at M = 1.5, 167 K (–106 °C) at M = 2, 107 K (–166 °C) at M = 3, and 71 K (–202 °C) at M = 4. The duration of such conditions is short, though, because of the limited run time, and measured in seconds.

Thermal influences on in-model instrumentation in the T-38 wind tunnel

Thermal influences on wind tunnel balances

During a run in a blowdown wind tunnel, internal wind tunnel balances operate in the conditions of varying ambient temperature. Effects of these variations on the balances (and other transducers based on strain-gauge bridges) are manifested as changes of zero-offsets (output signals at zero loads), as changes of sensitivity, and as apparent loads caused by thermal gradients. Changes of zero offsets are caused by minute differences in thermal characteristics of the strain gauges forming the Wheatstone bridges. Changes of sensitivity are the combined effect of the temperature-related variations of the modulus of elasticity of the balance material and of the gauge factor of strain gauges. Apparent loads due to thermal gradients are a consequence of strains in the body of a balance caused by different thermal expansion of body parts in the conditions of a non-uniform temperature distribution. Techniques have long-since been developed to reduce the thermal shifts of zero offsets and sensitivity of strain-gauge balances [1, 8, 16]. They involve matching of strain-gauges and placing of suitable compensation elements in the bridge circuits. These techniques, however, assume an equilibrium thermal state of the balance at a uniform temperature and are not very effective when the balances are subjected to temperature gradients, for which there is yet no satisfactory solution, so that this problem is still an object of research [9, 14, 17].

The common thermo-compensation techniques are usually sufficient to ensure a good quality of force measurements in the T-38 wind tunnel of the VTI. Recently, however, in a test campaign comprising unusually long sequences of supersonic tests at the Mach numbers 2, 2.5, and 3, it was observed that the temperature-induced zero shifts on fin-panel and wing-panel balances on the model were unacceptably large, although the strain gauge bridges on the balances were thermally compensated in the usual way and within the accepted tolerances of 0.06 μV/K per Volt of bridge excitation [10, 16]. The problem was aggravated by the space constraints in the design of the balances, which resulted in very stiff flexures and small full-scale signals for some components and barely sufficient stiffness for other components. Observed behaviour was similar to that reported [14] for the panel-force balances at similar conditions in another wind tunnel facility – NASA Langley Research Center Unitary Plan Wind Tunnel.

Except for some temperature measurements on one main balance, no data existed on thermal conditions inside typical models in the T-38 wind tunnel. Therefore, to obtain a better understanding of the thermal effects occurring in the spaces where the force-balances are located, sensors for interior-temperature measurements were added to test set-ups for two wind tunnel models, *i. e.*:

– In the wing-panel-balance space (fig. 7) of the 65 mm diametre winged-missile model on which large thermal effects on three-component wing- and fin-balances were observed. Temperature sensor was placed close to the three-component balance that was produced integral with a model wing, beneath a 0.5-mm thick balance cover on the model. Unfortunately, because of the limited space in the model, it was not possible to place a sensor near the fin-balance as well;

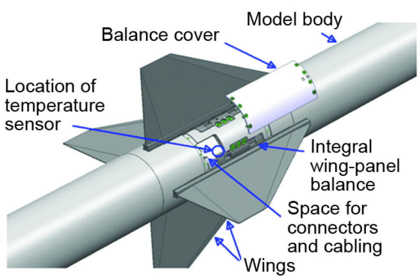

Figure 7. Position of the semiconductor temperature sensor in the wing-balance space in a winged-missile model

– In the main-balance space of a 75 mm diametre standard HB-2 wind tunnel model [18], at the rear end of the main Able/Task six-component balance, fig. 8. Temperature sensor was

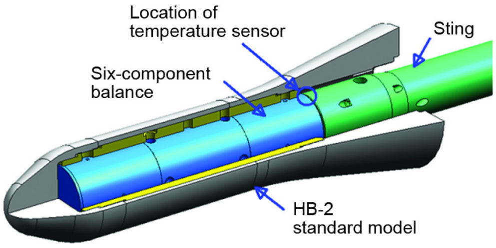

Figure 8. Position of the semiconductor temperature sensor in the main-balance space of a HB-2 standard wind tunnel model

cemented in front of the face of the sting support of the model, in the space between the sting and the balance.

All wind tunnel runs with the two models were of a similar duration (22-25 seconds, depending on flow-stabilisation time at a particular Mach number) and were performed at similar dynamic pressures of 90-100 kPa.

One LM335 semiconductor sensor with a linearized output of 10 mV/K was used to measure model interior temperature. Plastic TO-92 housing of the sensor was grinded-down to approximately 30% of the original size in order to reduce the time constant of the device. While it was recognized that the reaction time of the used sensor was quite long, this device was selected because of the simplicity of connecting it to wiring available in the model, as it was not practical to install faster-reacting sensors like thermocouples in test set-ups already mounted in the wind tunnel.

Stagnation temperature of the air was measured by a probe in the settling chamber of the wind tunnel, using a thick-film OMEGA 100W30 platinum RTD (resistance temperature detector) sensor.

The results of temperature measurements are given in figs. 9-14 where variations of model-interior temperature, T_m, are plotted along the variations of settling-chamber stagnation temperature, T_0, and test-section stagnation pressure, P_0. Figures 9-11 show T_m in the wing-balance space of the winged missile model at Mach numbers 1.5, 2.5, and 3, respectively. Figures 12-14 show T_m at the rear end of the main six-component balance in the wind tunnel test of the HB-2 standard model at Mach numbers 1.6, 2.5, and 3, respectively.

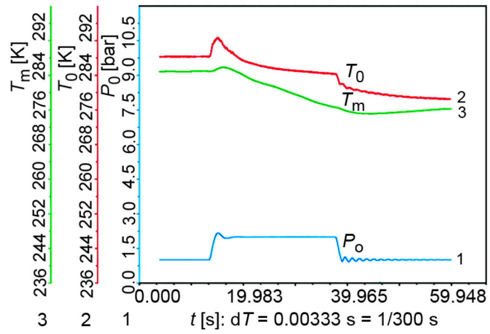

Figure 9. Variation of model interior temperature in the wing-balance space of the winged-missile model at M = 1.5, P_0 = 200 kPa

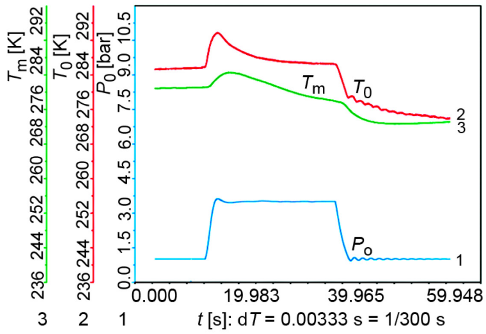

Figure 10. Variation of model interior temperature in the wing-balance space of the winged-missile model at M = 2.5, P_0 = 350 kPa

Measurements showed that the variations of temperature in the interior of typical models in supersonic runs were characterized by an increase at the beginning of the run, followed by a slower temperature drop during the run, thereafter followed, at the end of the run, by a larger temperature drop. Variation of model interior temperature followed the character of the variation of the stagnation temperature of the airflow.

The initial increase of temperature and the temperature drop at the end of each run were due to the near-adiabatic compression and expansion of the air in the wind tunnel tube at the start and the end of the run. The magnitude of effects increased with the Mach number, because the operating stagnation pressures and, thus, the magnitude of rapid pressure changes, increased with the Mach number.

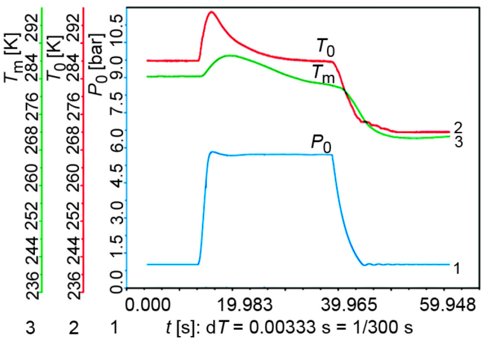

Figure 11. Variation of model interior temperature in the wing-balance space of the winged-missile model at M = 3, P_0 = 570 kPa

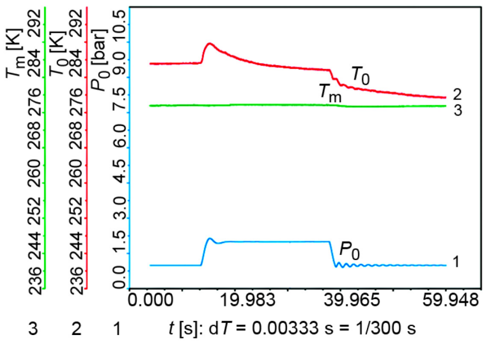

Figure 12. Variation of model interior temperature at the rear end of the main balance in the HB-2 model at M = 1.6, P_0 = 200 kPa

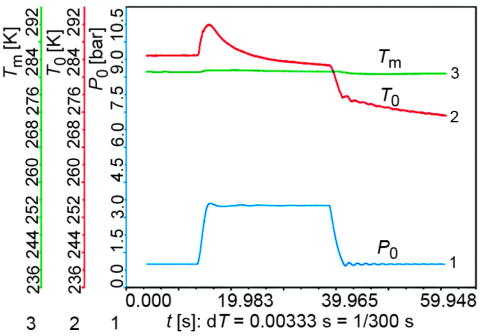

Figure 13. Variation of model interior temperature at the rear end of the main balance in the HB-2 model at M = 2.5, P_0 = 350 kPa

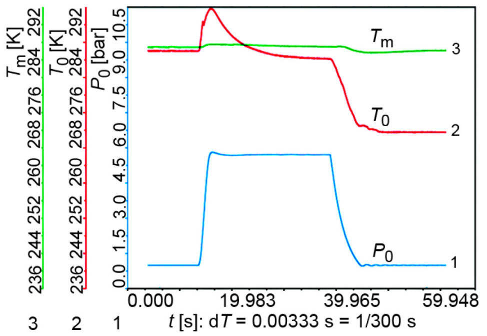

Figure 14. Variation of model interior temperature at the rear end of the main balance in the HB-2 model at M = 3, P_0 = 570 kPa

Differences that can be observed between the initial model-interior temperatures and initial (pre-run) stagnation temperatures were caused by different ambient conditions around the model and around the stagnation-temperature probe in the settling chamber. The T_0 probe in the settling-chamber was relatively secluded inside the high-thermal-capacity volume of the chamber. Besides, the air entering the settling chamber from the storage tanks generally showed a small, gradual, increase of temperature during a work-day of intensive operation. On the other hand, the model area was repeatedly exposed to ambient conditions in the wind tunnel hall, as the test section was opened for interventions on models between the runs, and was also, to a certain extent, exposed to external wintertime atmospheric conditions, being separated from the outdoors ambient only by the diffuser and the exhaust of the wind tunnel, fig. 1. Therefore, contrary to settling-chamber temperature, the temperature in the model area either remained more-less constant or dropped during a workday.

From figs. 9-14 it can also be observed that the variations of model interior temperature were larger in the wing-balance space than in the main-balance space. Temperature variations between pre-wind-on and post-wind-on conditions in the wing-balance area, close to the surface of the model and the large wing panels, ranged from approximately 9 K at M = 1.5, to 15 K at M = 3. In-model temperature drops during the wind-on measurement phase of the runs were similar in all observed runs, about 10 K, regardless of the Mach number. Moreover, at M = 1.5 in-model temperature mostly dropped below the initial value (fig. 9) while, at the other extreme, at M = 3, temperature first increased and then dropped (fig. 11) so that the maximum deviation from the initial value was about 50% smaller than at M = 1.5. With the full-scale signals of about 0.6 mV/V and bridges compensated to 0.06 μV/VK, temperature change of 10 K should have resulted in zero shifts of 0.6 μV/V so that the thermal zero-shifts should have caused measurement errors of approximately 0.1% of full scale. Observed measurement errors, however, were larger and were attributed to the apparent loads caused by rapid temperature changes of about 0.5 K/s and thermal gradients in the body of the balance.

The sudden drop of temperature (about 10 K) at the end of runs at higher Mach numbers was found to be an additional problem. Figures 10 and 11 show that most of the cooling of model interiors at higher Mach numbers occurred not during the actual wind-on runs but after them, and that the return to *normal* ambient conditions lasted for a considerable time. This meant that, if the time interval between runs was too short, the models entered each subsequent run at lower and lower body temperatures so that in each following run the in-model instrumentation suffered larger temperature-induced deviations from the nominal conditions and, besides, was not in thermal equilibrium at the start of the run. It was empirically found that an interval of more than one hour between two runs was needed for the in-model instrumentation to re-stabilize at the ambient temperature conditions.

Variations of temperature of the main balances were more than an order of magnitude smaller, generally below 1 K (figs. 12-14) and, regarding the changes in one run only, could be termed negligible. However, cumulative effects of cooling after a series of high-Mach supersonic runs could be observed here as well. Similar magnitude of temperature changes had been observed, but not investigated, in an earlier test [19] with a balance that incorporated a temperature sensor.

The problem of ambient-moisture condensation

As seen from *e. g.* figs. 10 and 11 the temperature of the model parts close to its exterior surface can drop significantly below the room temperature after a sequence of supersonic runs in the T-38 wind tunnel, and can reach sub-zero values. As, after a wind tunnel run, a model is exposed to atmospheric air through the diffuser of the wind tunnel (fig. 1), it is often that the model temperature comes below the dew-point of the surrounding air and the condensation of the moisture from air occurs. Moreover, it is not uncommon that the model becomes covered with a thin layer of frost immediately after a high-Mach run. This condensation and deposition can present a problem for in-model instrumentation as it is known that the strain gauge bridges on wind tunnel balances are susceptible to influences of ambient humidity. Therefore, moisture-proofing of the strain-gauge areas on wind tunnel balances is a normal practice, but it can be impractical to apply to miniature electrical connectors or wire-terminal strips that have to be disconnected and reconnected a number of times when changing the model configurations during the course of a wind tunnel test campaign.

Reducing the problems caused by temperature changes

Thermal behaviour of a blowdown wind tunnel like the T-38 is a characteristic of the type of the facility and can not be changed. Therefore, all tests must be designed having in mind the occurrence of significant temperature changes.

Performed temperature measurements indicate significant temperature gradients inside the model volume and in the bodies of internal wind tunnel balances. Such behaviour seem to favour the choice of moment-type and force-type internal balances over the direct-read ones, as, with the first two types, all strain gauges from one Wheatstone bridge are usually located close one to another and are less likely [20] to become unbalanced by the temperature gradients.

It is also conceivable that the thermal effects on zero offsets and sensitivities of the wind tunnel balances can be reduced by software techniques. Indeed, when the T-38 wind tunnel was built and commissioned, it was recognized that thermal influences on in-model instrumentation could be expected, and certain provisions for compensation of these effects were made. Procedure for the wind-tunnel runs in the T-38 included a pre-wind-on (pre-tare) and post-wind-on (post-tare) recordings of all transducer outputs. Routines in the data-reduction software provided either a linear interpolation or a mean value for zero-offsets in wind-on measurements between the pre-tare and post-tare recordings. However, it was soon observed that this technique produced worse results than if no compensation was made and it became normal practice to use only the pre-tare recordings to obtain initial zero-offsets values before the run. The measured pre-tare values were then applied to all run data.

Figure 15 shows the reason for the failure of the initial compensation algorithm. The graphs in the figure show variation of interior model temperature, T_m, in 23 seconds runs at M = 2.5, P_0 = 350 kPa, and M = 3, P_0 = 570 kPa in comparison with the temperature, T_E, deduced by the initial zero-drift-compensation algorithm in the data-reduction software that relied on interpolation from pre-tare and post-tare recordings. It is obvious that the compensation algorithm did not realistically model the complex actual variations of temperature. Compensation on the basis of mean values between the pre-tare and the post-tare produced even worse results. A better solution of the problem appears to be to measure at least an averaged balance-body temperature during a run and to correct the offset- and sensitivity-shifts on the basis of such measurement. It was concluded that this could be done with relative ease by introducing the balance body temperatures as additional measuring components of the internal

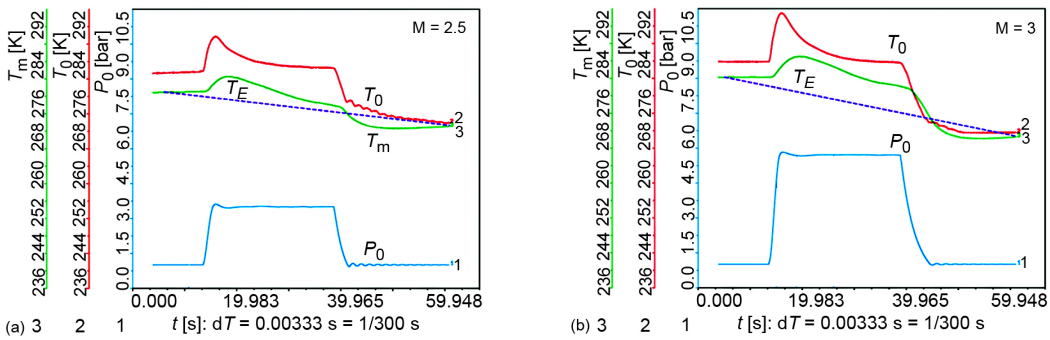

Figure 15. Comparison of observed variations of interior model temperature T_m in a Mach 2.5 run at P_0 = 350 kPa and a Mach 3 run at P_0 = 570 kPa with the temperature corrections T_E deduced by the abandoned pre-tare/post-tare compensation algorithm

balances [21]. Calibration matrices of the balances would, therefore, contain additional temperature related data. Balance calibration would include loadings at several ambient temperatures and the appropriate terms in the calibration matrices would be determined by the global-regression method [20]. Provisions for this method already exist in the balance-calibration software used at the site, which can handle balances with up to eight components, while the modifications of the wind tunnel data reduction software are in progress. The proposed method, in its simplest form, would compensate only thermally-induced in-run deviations of sensitivity and zero-offsets relative to pre-tare conditions, but not variations of the bridge sensitivities related to change of the absolute temperature. Therefore, stable pre-run conditions at near-ambient temperature would be required.

Thermal re-stabilization of in-model instrumentation between wind tunnel runs was shown to be important and necessary in order to obtain satisfactory test results. This can be achieved by prescribing an obligatory time interval between supersonic runs, even when the air consumption *vs.* the tanks-charging rate would permit a higher run frequency. Unfortunately, such strategy has a negative effect on the productivity of the facility as it can reduce the number of runs in a work-day by more than 30%. A practice was introduced, therefore, of acquiring balance zeros at intervals during a workday, to access their time histories and to help in planning of run schedules if necessary.

Depending on the meteorological conditions, a further stabilization of model temperature and a reduction of moisture condensation could be achieved by isolating the test section from the outdoor air. In the T-38 wind tunnel this could be easily achieved by completely closing immediately after a run, and opening prior to the next run, the sidewall flaps that form the second throat (fig. 1) downstream of the test section. However, because of the safety concerns about completely closing the wind tunnel exhaust when the air tanks are pressurized, this idea was not put into practice.

Conclusions

The operating concept of the supersonic blowdown wind tunnel creates temperature variations which influence the measurements performed in such installations. As these temperature variations can only be reduced by wind tunnel design but not be eliminated, they must be considered in the planning of wind tunnel tests in order to perform valid measurements in their presence. Knowledge of the character and magnitude of temperature variations around in-model instrumentation is essential in this matter. To such end, the authors have performed measurements of temperature variations inside wind tunnel models tested at supersonic Mach numbers in the T-38 blowdown wind tunnel.

Experiments showed that the variations of temperature were minor (less than 1 K) in the ambient of the main balance in a typical wind tunnel model but were about an order of magnitude larger in the area of the panel-force balances closer to model surface. Temperature--induced measurement errors of panel-force balances were even larger than expected from the magnitude of temperature changes and were attributed to temperature gradients. Therefore, it was concluded that the main balances operate in thermally stable conditions that permit even the use of devices that are known to be pronouncedly temperature-sensitive, such as *e. g.* semiconductor strain gauges. On the other hand, utmost care should be exercised in the design, production and thermo-compensation of panel-force balances for future tests. For thermal stability, strain-gauge wiring designs such as the moment- and force-types, where the strain gauges forming the bridges are closely grouped, should be preferred to direct-read designs. Inclusion of at least one temperature sensor in each new panel-force balance is strongly recommended, and the changes of the data-reduction software for the VTI wind tunnels, which are in progress, will permit inclusion of temperature-related calibration data in the calibration matrices so that correction of temperature effects will be possible.

Test procedures will have to be modified, limiting, in tests with panel-force balances, the frequency of supersonic runs to no more than one per hour, and test schedules will have to be planned accordingly. Monitoring of between-the-runs changes of zero offsets was shown to be useful and is to be continued.

Nomenclature

L_m – length of thermal matrix, [m]
M – Mach number
n – polytrope exponent
P_0 – stagnation pressure, [kPa]
P_f – final pressure in the air tank, [kPa]
P_i – initial pressure in the air tank, [kPa]
P_t – pressure in the air tank, [kPa]
T – airflow static temperature, [K]
T_d – temperature aft of thermal matrix, [K]
T_E – estimated corrected temperature, [K]
T_f – final temperature in the air tank, [K]
T_i – initial temperature in the air tank, [K]
T_m – model interior temperature, [K]
T_0 – stagnation temperature, [K]

Greek symbol

κ – ratio of specific heats

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