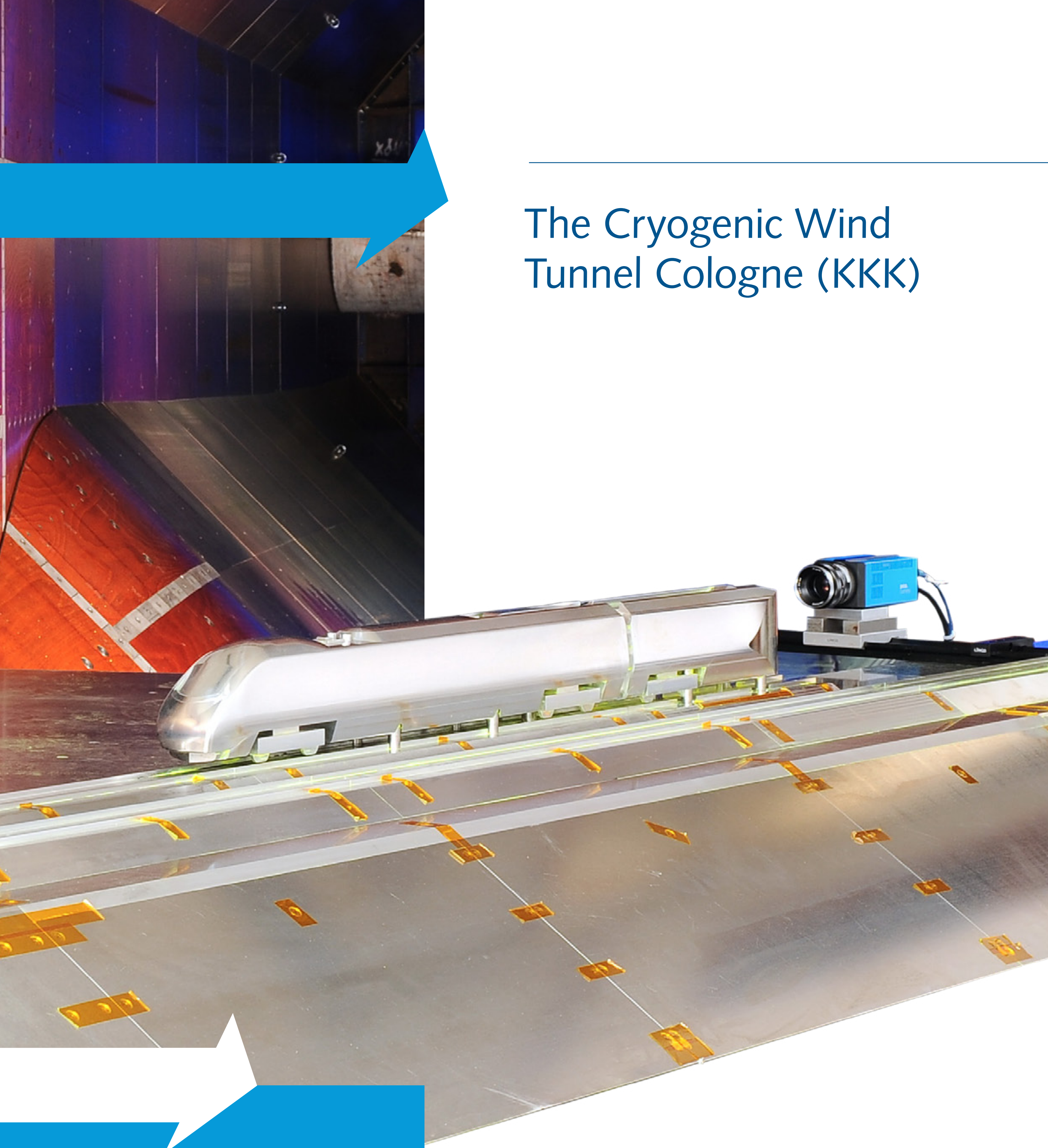
The Cryogenic Wind Tunnel Cologne (KKK)



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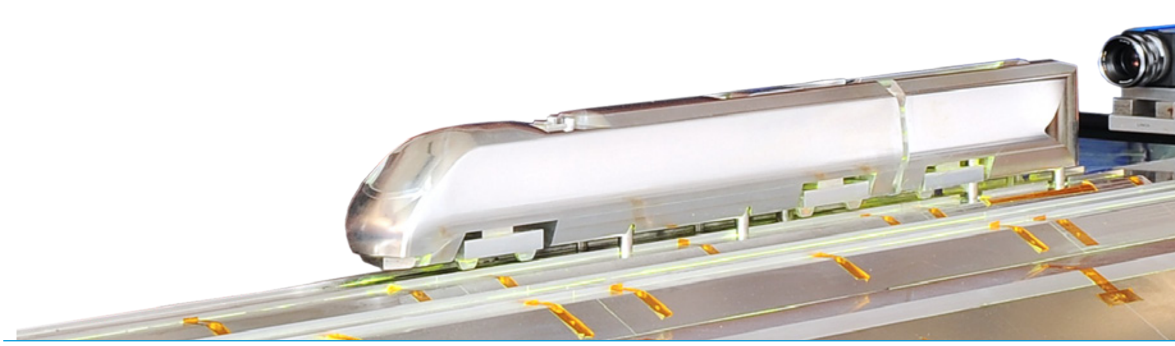


The Cryogenic Wind Tunnel Cologne (KKK) is a closed circuit low speed tunnel. To achieve high Reynolds numbers, the gas temperature in the tunnel circuit can be lowered down to 100 K by injecting liquid nitrogen.

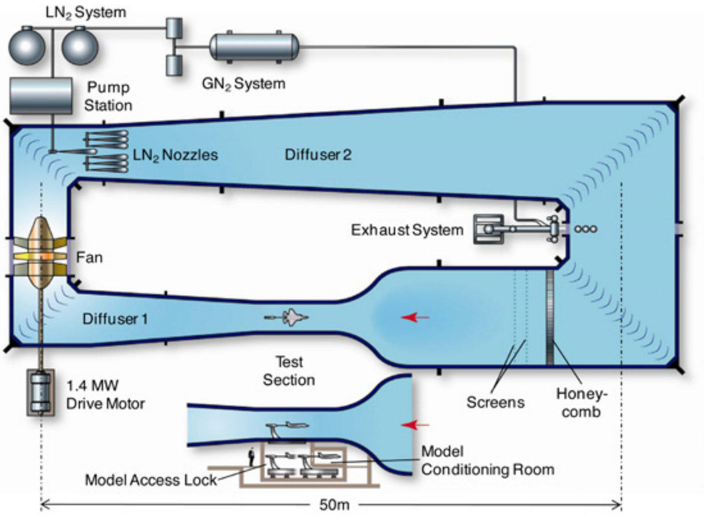
Key Technical Parameters

Test section: 2.4 m × 2.4 m × 5.4 m
Fan power: 1.4 MW
Contraction: 10.4

Stagnation pressure: atmospheric
Dynamic pressure (max): 1.1×10^4 Pa
Temperature range: 100 K ÷ 300 K

Mach no. (max at 300 K): 0.34
Mach no. (max at 100 K): 0.40
Reynolds no. (max, l_{ref} = 0.24 m): 10×10^6

Figure 1
Wind Tunnel Circuit



The Reynolds number can be thus increased by a factor of 5.5 while the drive power remains constant (see Figure 2). Due to the possibility of independent variation of the gas temperature and flow velocity, the influence of the Mach number and Reynolds number on the aerodynamic characteristics can be investigated separately.

Tunnel operation, test parameters, and the measurement and data acquisition are automatically controlled by an integrated hard- and software system.

Test Section Area

The test section area consists of the test section itself, the model access lock and the model conditioning room. Both sidewalls of the test section are equipped with a modular system of exchangeable windows to enable application of flow visualization and optical measurement techniques. Furthermore, two rows of pressure taps are located on each wall to measure the static pressure distribution necessary for wall interference correction.

The access lock and the model conditioning room are located underneath the test section. They allow model changes at ambient temperature while the tunnel is maintained at cryogenic temperature. In this way high productivity can be achieved.

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The lock and the model conditioning room both have individual temperature control systems provided by nitrogen and dry air injection and enforced heating. In this manner they can also be used as independent cryogenic (pre-)test facilities.

Test Capabilities and Measurement Techniques

Due to its Reynolds-Mach capability the KKK is an outstanding wind tunnel for high lift low speed take-off and landing configuration testing of all kind of aircraft as well as for fast ground vehicles like high speed trains. For this there are three different model support systems:

- A three-dimensional (3D) model cart can handle models with a maximum wing span of 1.5 m. Based on a 3D model reference length of 0.19 m the maximum Reynolds number 7.3×10⁶ can be simulated. Models are mounted on a sting (see Figure 9).

- The 2D airfoil model cart carries models with a chord length up to 0.7 m and a span of 2.4 m. The maximum Reynolds number can reach 27.1×10⁶. The models are mounted in synchronized turntables on the top and bottom walls (see Figure 5).

- Half models are mounted on the half model support which consists of a turntable with a heated balance inside (see Figures 7 and 8). The maximum Reynolds number, formed with a reference length of 0.4 m is 15.5x10⁶.

All three supports, together with the models installed, can be lowered into the lock below the test section. 2D airfoils have to be disconnected from the upper turntable link before lowering.

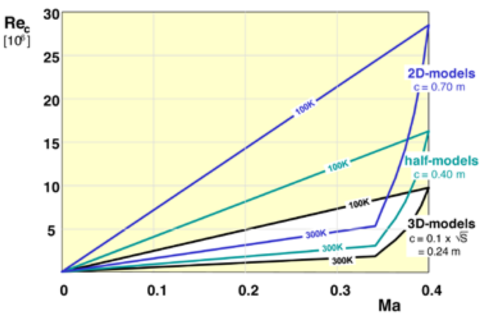


Figure 2

KKK is capable of simulating high Reynolds-numbers by lowering temperature.

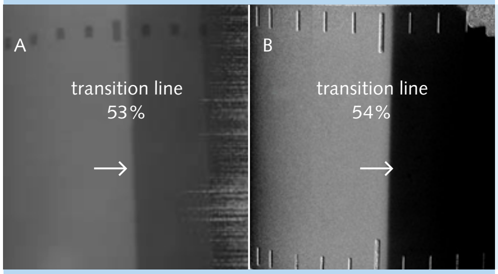


Figure 3

A. Transition detection using Infrared Imaging.

B. Transition detection using Temperature Sensitive Paint.

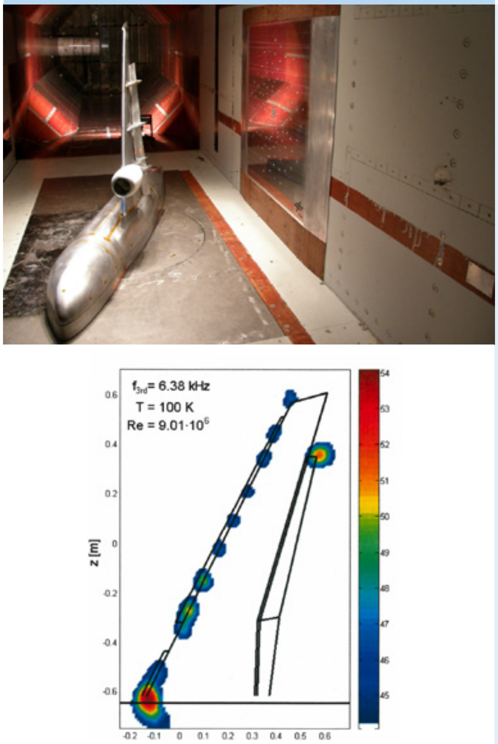
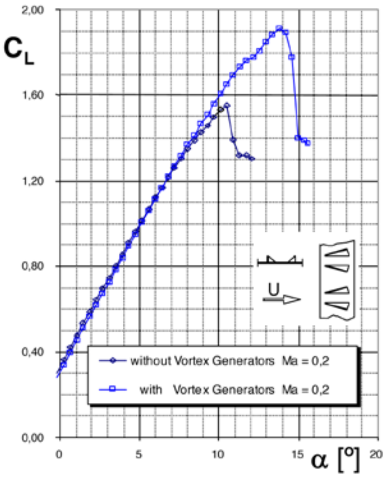


Figure 4

Acoustic measurements with a 9.24% scaled half-model of the Dornier-728.

Figure 5
Increase of maximum lift of a thick wind rotor airfoil by application of vortex generators.



Internal six-component balances and a five-component half model strain gauge balance are used for force measurements and a temperature compensated electronic pressure scanning system (PSI) for pressure measurements. For surface flow visualization the CO_2-sublimation method, colored oil, mini-tufts, and infrared imaging can be used. Flow field data can be acquired by pitot and five-hole probe rakes on a traversing mechanism and by a particle image velocimetry system (PIV, obtainable from DLR).

For transition detection infrared imaging and temperature sensitive paint (TSP) can be used (see Figure 3). The best result for TSP imaging can be acquired in the temperature range from 100 to 200 K, while for infrared from 200 K to ambient.

For aero-acoustic measurement a cryogenic microphone-array containing 144 electret microphones can be used. Figure 4 shows acoustic array measurements performed at Reynolds number of $9x10^6$ using a 9.24% Dornier-728 half model. The tests indicated different source mechanisms at the same Mach and Strouhal number but for different Reynolds numbers.

2D-Airfoil Testing

Testing of 2D-airfoils in KKK can provide significant information. Even for large transport aircraft the take-off and landing configurations with high lift devices like flaps and slats and other kind of flow control devices can be simulated at realistic Reynolds and Mach number conditions. The duplication of these parameters is especially necessary for correct drag and maximum lift measurement where the boundary layer plays a dominating role.

Both turntables in the upper and lower tunnel walls are synchronized to prevent distortion. Tangential blowing through slots on the turntables in front of the airfoil improves the twodimensionality of the flow. The integral lift, drag, and pitching moment are determined from the pressure distribution on all airfoil elements and from the total pressure loss in the wake. The latter is measured with a pitot rake.

Figure 5 shows an example of flow control test results in KKK. The thick airfoil was designed for a wind rotor blade. A small metal band with triangles punched out and bent upwards was glued to the model surface, to form a row of vortex generators. As they are designed to manipulate the boundary layer, the effect on the flow is strongly depending on the correct Reynolds number duplication. In this case the maximum lift

Half model simulation technique is widely used

is considerably increased and thus the behavior of stall controlled wind rotors is affected.

Half Model Testing

To examine trim conditions and high lift systems of aircraft configurations in symmetric flow, the half model simulation technique is widely used. This reduces model costs and permits a larger scale with the benefits of better detailing and a higher Reynolds number. The effectiveness of control setting and design can be studied by high precision measurement of differences between different configurations. The mechanical angle of attack range is ± 30°.

The standard total force and moment measurements with the heated underfloor balance are typically supplemented by pressure measurements and video recordings of mini-tufts. The flow field can be analyzed by traversing pressure probes and probe rakes or by use of optical methods like laser light sheet (visualization) and Particle Image Velocimetry (PIV).

The vector-field diagram in Figure 6 shows the vorticity distribution and the cross flow velocity components in a plane behind the wing tip, measured using a five-hole probe rake (see Figure 6). Similarly, even more detailed information can be achieved using PIV, as shown in Figure 12 of the lee side of a train.

Nacelle to wing interferences of jet aircraft are simulated by through-flow nacelles (see Figure 8). For turboprop simulation cryoproof electrical motors fitting into half model nacelles are available. They are designed for maximum continuous shaft power of 12.5 kW at 9000 rpm. This, for example, permits the simulation of take off and landing of the A400M.

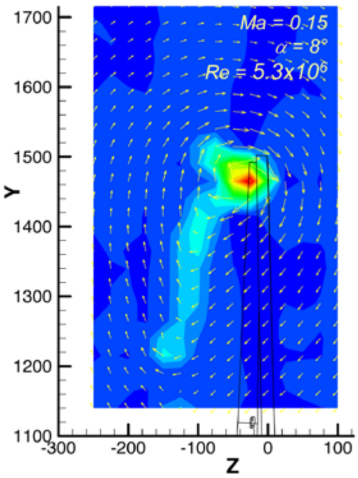


Figure 6

Wing tip vorticity distribution-five-hole probe rake results.

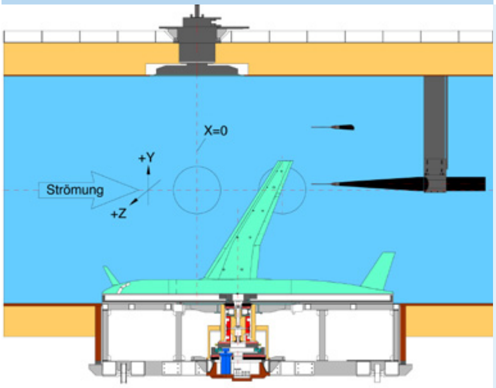


Figure 7

Half model support with five-component balance, wake probe, and rake traversing system.

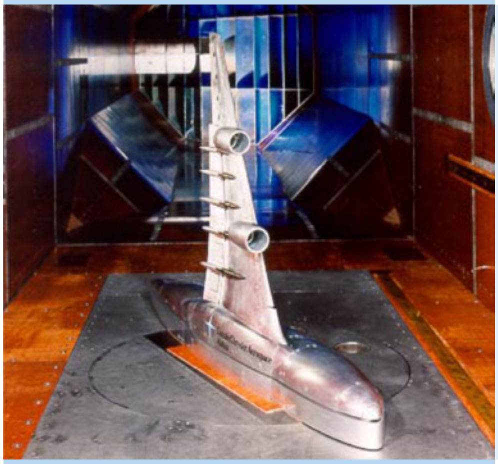


Figure 8

Large transport aircraft half model-high lift configuration with through-flow nacelles.

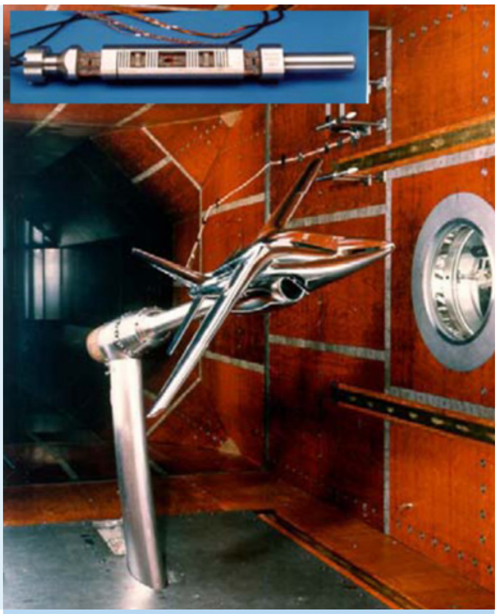


Figure 9
Alpha-Jet model on the 3D support and cryogenic internal six-component strain gauge balance.

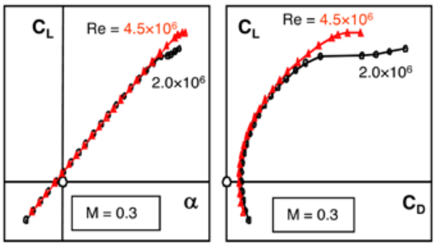


Figure 10
Lift curves and drag polars of a fighter configuration.

3D-Aircraft Testing

The standard 3D support of the KKK consists of a –10°<α<30° sword on an underfloor jack, a –90°<ϕ<90° roll angle mechanism, and rearward sting for model suspension. For six-component force and moment measurements cryogenic (not heated) internal strain gauge balances are available to be used in the complete temperature range 100 K < T < 300 K (see Figure 9). The actual angle of attack is controlled by an internal heated inclinometer. All measurement techniques used in airfoil and half model tests, e.g. surface and wake pressure probes, flow visualization, and PIV can be applied in full model testing as well.

The lift curves and drag polars of a fighter configuration shown in Figure 10 were measured in the KKK. The findings of airfoil and half model tests are confirmed: not only does the drag depend on the Reynolds number; even more important are the Reynolds number effects on the stall behavior in the high angle of attack region. Here the correct Reynolds number simulation seems mandatory.

Ground Vehicle Testing

For the aerodynamic analysis and design of ground vehicles like cars, trucks and trains Reynolds number effects can be significant. Automobile models at 1:5 scale can be tested at the original Reynolds number in KKK. Trains are tested on the half model support (see Figure 11); the scale is normally restricted to 1:20, in order to fit the model to the tunnel lift system and to allow reasonable angles of sideslip. Increasing the tunnel speed can produce Reynolds numbers close to the original.

The correct ground simulation for trains in wind tunnel tests is always a matter of compromise. In KKK the model is mounted over a split plate. The internal six-component balance and the pressure measurement system, alongside with the PIV technique, designed for high precision aircraft tests, are suitable for train simulations as well. The two PIV-pictures in Figure 12 reveal details of the leeside vortex shedding of a yawing

> The cryo-technique, in contradiction to pressurized tunnels, has the advantage of not raising the pressure load on the model

high speed train. They are recorded at a tunnel temperature of 100K and Mach number of 0.2. The model in the upper picture is clean, while the model in the lower picture is dimpled. The effect of dimpled surface is obvious.

Cryo-Model Requirements

The cryogenic environment down to 100 K requires the choice of an appropriate material. The strain due to temperature gradients should be low. The corresponding coefficients of all different materials used in one model have to be close to each other. On the other hand, the cryo-technique, other than in pressurized tunnels, has the advantage of not raising the pressure load on the model. Compared to pressurized transonic wind tunnels the loads are much lower. So models of special aluminum (3.4345.71), steel (1.4301), or of CFRP (carbon fiber reinforced plastic) have been proven to be a good choice for KKK tests, even for detailed structures like high lift devices. They need not be more expensive than for conventional tunnels.

The surface quality of models has to be adapted to the thin boundary layers corresponding to a high Reynolds number. KKK provides heated boxes for PSI-modules and other instruments to be integrated into the model.

Operation, Productivity

Thermal insulation leakages require a continuous expenditure of LN_2. Cooling down and heating up of the wind tunnel takes time. The reduced accessibility through the lock system extends the configuration change time. These drawbacks are compensated by a multiple shift operation five to six days a week, resulting in a productivity of about 15 configurations tested at cryo-conditions per week.

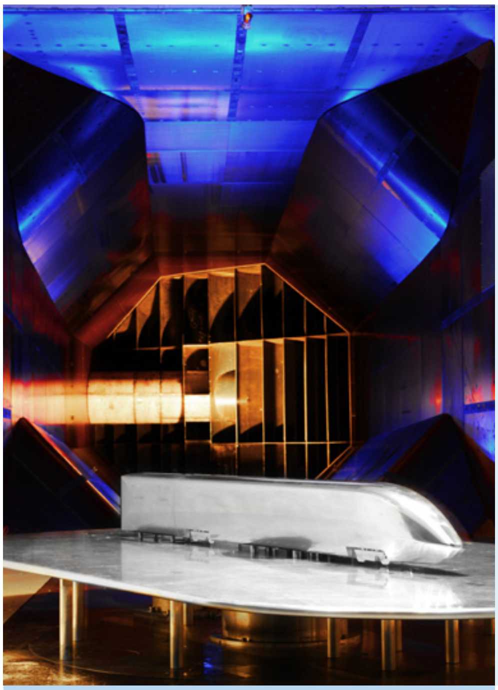


Figure 11
High speed train model on the half model support in KKK.

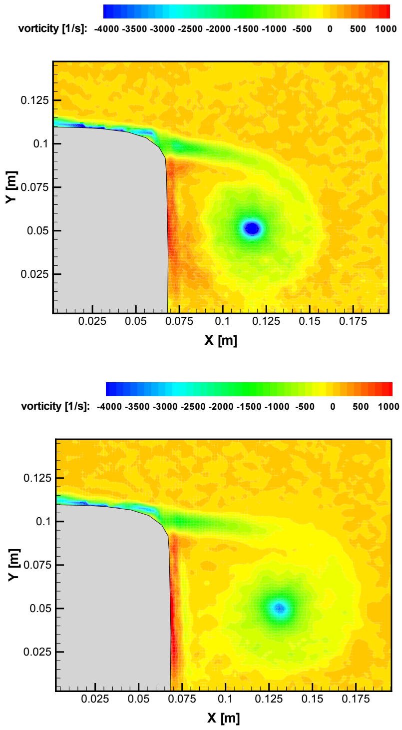


Figure 12
PIV-measurement of cross-flow streamlines at leeside of a yawing high speed train.

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