HeiDAS UH – Flying with superheated steam

A. Bormann[1] and S. Skutnik[2]
Technische Universität Berlin, Berlin, 10587, Germany

M. Fischer[3]
Festo AG & Co. KG, Denkendorf, 73770, Germany

[Abstract] The feasibility of steam as buoyant gas for high performing balloons was proved. Building and operating a rc-controlled insulated rozière-type model - HeiDAS UH became the first free flying steam balloon ever. Innovative and new developed materials are allowing temperatures up to 260°C and providing steam tightness and strength to the highest possible extend. CFD simulations of the entire balloon give a detailed overview of the temperature distribution and the efficiency of the insulation. A simplified mathematical model is presented which allows the quick and proper estimation of the thermal behavior and the systems performance. From the profound knowledge of the model an auomative altitude control system was developed and implemented. The steam balloon technology is now ready for implementation into a full scale prototype balloon.

I. Introduction

HEIDAS stands for HeißDampfAeroStat (Hot-Steam AeroStat) and it refers to the first operable balloon ever that became buoyant by means of superheated steam. The lift-performance of HeiDAS UH (UH = ultra-hot) ranks between that of a helium balloon and that of a hot-air balloon, however, HeiDAS UH uses a downright cheap, non-flammable, and invisible buoyant gas, which is steam. Steam shows almost three quarters of the buoyancy of helium and two and half times the buoyancy of regular hot-air balloons.

When beginning the multidisciplinary research on HeiDAS there was the question of what other and cheaper buoyant gas could be used for lighter-than-air aviation. Helium is expensive, whereas hot-air only facilitates payloads one third the amount of those for helium. This leads to voluminous, low-performing structures that are susceptible to winds. Hydrogen is less expensive and more powerful, yet it is flammable and therefore ruled out due to regulatory constraints. When the idea “steam?!” came up for the first time, it was smirked at initially, however, reflected more seriously afterwards. But what materials could resist steam, how do you keep up steam temperature, and how do you avoid steam condensing along the balloon envelope? As initial experiments showed, droplets of condensed water increased envelope weight, and hence, water had to be re-evaporated causing additional effort – effort that almost led to the abandonment of this novel approach.

Only through the application of a new, ultra-light and flocked insulation material superheated steam could be maintained also close to the envelope. In retrospect, this turned out to be the onset of one of the most exciting and comprehensive innovations of lighter-than-air aviation. In 2003, the first HeiDAS prototype was finished and successfully tested under laboratory conditions. However, it was not until the materials as well as the operational concept were further improved that initial outdoor-cruises became possible.

The second HeiDAS prototype is a novelty in terms of type and construction – it consists of an insulated gas-container holding 6.8 cubic meters of steam combined with a cone-shaped bottom part holding hot-air. A remote-controlled, adjustable propane-gas burner heats up the gas-container bottom, and thus, allows for heat loss compensation as well as vertical steering. Thanks to the insulation this prototype uses only a fraction of the fuel a regular hot-air balloon of comparable lift consumes. As far as we know, HeiDAS UH is the hottest aerostat ever rising up into the air. It provides a new and tangible vision concerning the field of lighter-than-air technology.

[1] Dr.-Ing., Institut für Luft- und Raumfahrt, Marchstr. 12-14 D-10587 Berlin, Germany.
[2] Dipl.-Ing., Institut für Luft- und Raumfahrt, Marchstr. 12-14 D-10587 Berlin, Germany.
[3] Dipl.-Ing., Corporate Design, Rechenbergstr. 3 D-73770 Denkendorf, Germany..

II. HeiDAS Design and Materials and Components

The HeiDAS-balloon is modeled after the Rozière-principle, that is, the buoyant gas is stored in a spherical and sealed container made from polymer film. The container is filled once before launch. In order for the steam to maintain its temperature of up to 150 °C during flight and to avoid condensation, the container is insulated and diffusing heat is recharged using a heat exchanger. Placed between heat exchanger and gondola, a propane super heater generates an adjustable hot-air stream which heats up the heat exchanger to 260 °C and more.

Similar to a hot-air balloon, buoyancy can be boosted through increased heat supply from the burner. Conversely, the balloon sinks if the buoyant gas cools down. Hence, unlike a gas-balloon there is no need for HeiDAS to carry along ballast weight as weight reduction during the cruise can be compensated for through steam and temperature control. As a result, the boost in buoyancy through the application of steam fully benefits an increased carrying capacity. Moreover, the necessary insulation reduces fuel consumption, and thus, makes up for its own additional weight especially during longer cruises.

A technical revolution was achieved not only through the application of steam but also by developing novel envelope and insulation materials and concepts.

A. HeiDAS Envelope Material

The HeiDAS envelope is made from flexible polymer films. In most cases, steam and high temperatures degrade plastic materials leading to brittleness and reduced stability. Although new materials, such as silicones and fluoric polymers are much more resistant, they aren't proof enough to hold back steam. A gas-tight silicone coating was applied with the first HeiDAS prototype that was able to even retain large amounts of air and helium. However, steam was permeating the membrane about 200 times faster than the much smaller rare-gas molecules, challenging the design team to develop an entirely new material

The result is the HeiDAS laminate – a polyimide film laminate reinforced by Aramid filament yarn. According to the design specifications, the HeiDAS heat exchanger is exposed to temperatures of up to 260 °C, which is tolerated not only by the polymer films but also the high-performance bonds made from Polysiloxan. The materials and bonds were pre-tested under high-temperature and steam conditions for more than 1000 hours. Even when exposed to combined thermal and mechanical stress, stability losses for both, materials and bonds were low and the remaining performance was still ways above minimal requirements. As such, all obstacles were cleared concerning the built of a model balloon prototype. Even temperatures of more than 310 °C over a short period of time during the tests didn't do any harm to the envelope. This was probably the highest temperature ever deliberately generated against a balloon envelope. The envelope of the HeiDAS UH prototype, thus, has been proven to not only resist degradation from steam and heat but to also prevent steam from permeating the membrane. The laminate allows only 25 g/(m^2 d) of steam to permeate which is equal to a loss of 1% of buoyant gas from a 600 cubic meter balloon in 10 hours and ensures the capability for long endurance flights. Reflective coating was applied to the polymer films in order to minimize heat loss.

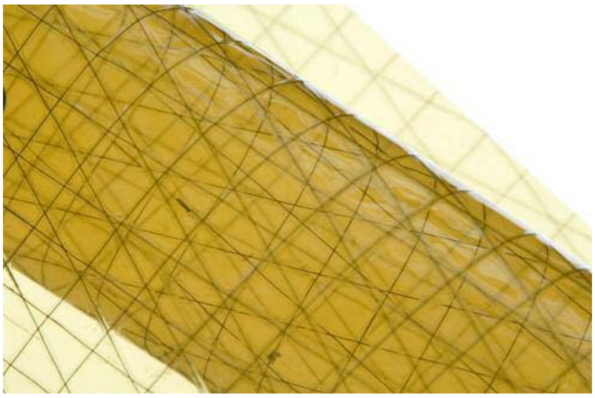

Figure 1: The HeiDAS laminate combines unmatched steam impermeability, high mechanical strength and temperature stability.

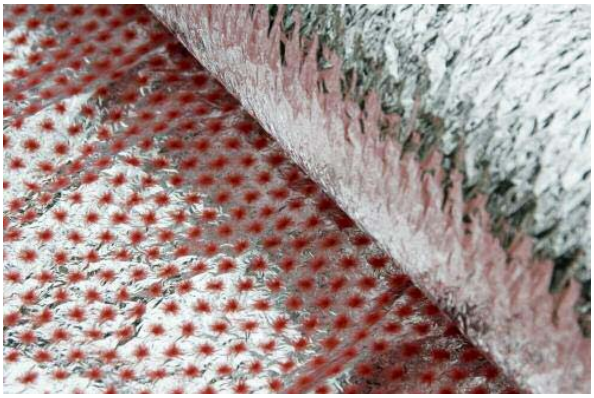

Figure 2: The new flock insulation shows low weight and thermal conductivity paired with unmatched reversible compressibility.

B. Super Insulation Flock Material

The HeiDAS development yielded the lightest and most powerful reversibly compressible insulation currently available. The new super-insulation-flock-material prevents steam from condensing along the inner-envelope and reduces the energy consumption necessary for keeping the buoyant gas at temperatures of up to 150 °C. The optimized insulation for HeiDAS weighs only 8.5 kg/m^3 and shows a very low thermal conductivity of just 0.035 W/(m K) even at high median-temperatures of nearly 100 °C. The super-insulation-flock-material consists of multiple membranes stacked evenly through flocked fibers. This generates a cluster of layers of air showing a thermal conductivity similar to that of steady air. HeiDAS is the prototypical application for the super-insulation-flock-material. Thanks to optimization work conducted at HeiDAS UH, the insulation necessary could be reduced from 21 mm to 7.5 mm in thickness. 7.5 mm is exactly the gap width, which shows the highest efficiency concerning a single layer of insulation; beyond that point, the insulating air shows an increased tendency for convection.

C. Balloon Burner with Swirl Nozzle

A typical standard balloon-burner system consists of tank, valve, supply hoses, super heater coils, and injection nozzles. The mixing of fuel and oxygen occurs in a quasi open combustion chamber after the propane gas exited the nozzle. Developing HeiDAS required the design of special burner, for the Rozière-construction allows for only a small distance between the gondola and the balloon envelope around the heat exchanger. With regular pointed flames the local temperature peak would be either too high or, when throttling the burner, the resulting heat flow would be too low. As such, the custom designed HeiDAS UH-burner uses particular nozzles allowing for better mixing of fuel and air, and thus, improving the flame pattern as well as temperature distribution around the heat exchanger. Efforts to minimize burner size hit technological limits when it came to designing nozzles of less than two tens of a millimeter in diameter. Moreover, these efforts were not only directed at improved power ratings but weight reduction as well. As a result, the HeiDAS UH-burner tops all comparable burners existing – weighing only 58 grams at a power output of 70 kW.

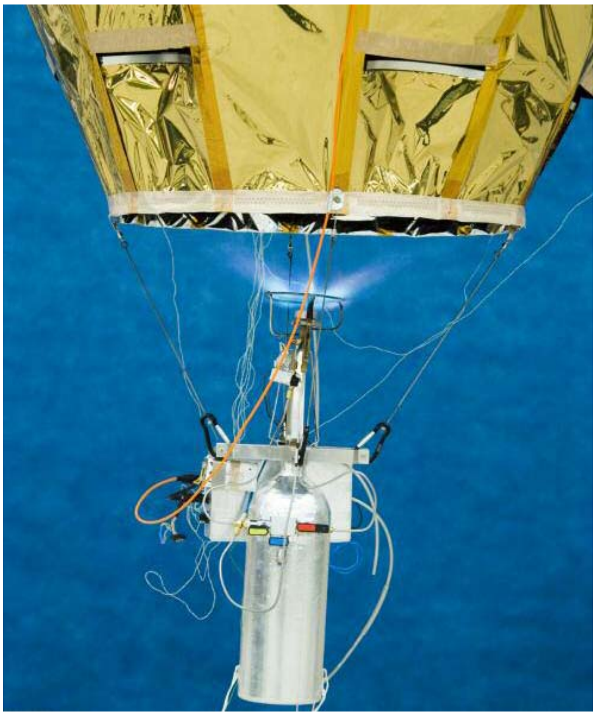

Figure 3: Gondola with onboard computer and swirl burner.

D. The HeiDAS Onboard Computer

A 16bit micro-controller uses an internal 12bit-analogue-digital converter to track data on temperature, gas pressure, altitude, and vertical velocity as well as acceleration. Also, it analyzes the data and subsequently conveys it to a PC on the ground by means of a safe digital radio link (DECT standard). Ultimately, the ground-PC records and displays the performance data. The balloon can be controlled either via a standard remote control – as used for model planes – or via the ground-PC attached to the DECT radio link. Using the manual mode, the balloon can be maneuvered directly by managing the burner as needed. In automatic mode, certain cruising parameters, such as altitude or climb/sinkrate, can be preset and automatically commanded by the microcontroller as well as an integrated control unit. The microcontroller also covers critical safety features – e.g. it shuts down the burner if the temperature exceeds the approved limit of 260 °C. Similarly, the burner stops and a pressure valve opens as soon as the internal pressure hits 500 Pa.

III. Test Results

Numerical calculations were conducted using different methods and model detail as published in References 1-3. Those results were compared with measured data from indoor test flights with the first prototype and show good

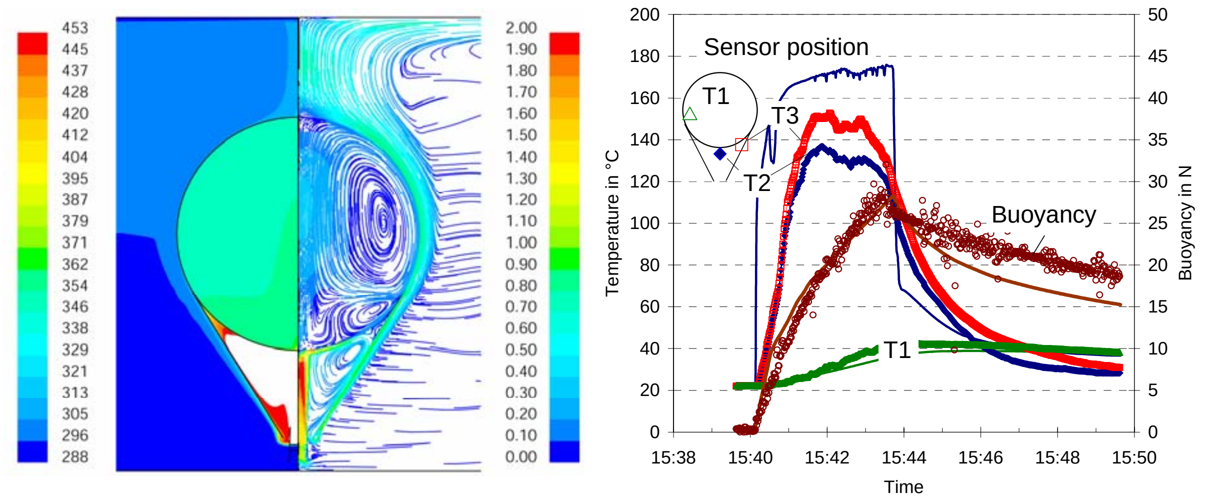

Figure 4: Simulated temperature distribution (°K) and streamlines colored by velocity magnitude (m/s) (left), comparison of simulated and measured values of temperature and lift during a heating/cooling maneuver (right).

accordance with measurements[4] with respect to integral values (e.g. lift, power consumption) but tend to overestimate local maxima of for instance the temperature. Figure 3 shows calculated temperature and velocity field for a selected calculation. It also shows the quite good match between calculated and measured time dependent behavior of the balloon.

However, despite the good prediction of the balloons behavior a full CFD calculation is too time consuming for preliminary design involving optimization.

Therefore, a low-parametric model was build[5,6]. This model uses only six temperatures to describe the thermodynamic state of the balloon and matches well with the results of the CFD calculations. This is shown exemplarily in Figure 4 which displays the comparison between temperatures derived from the low parametric model and CFD calculations.

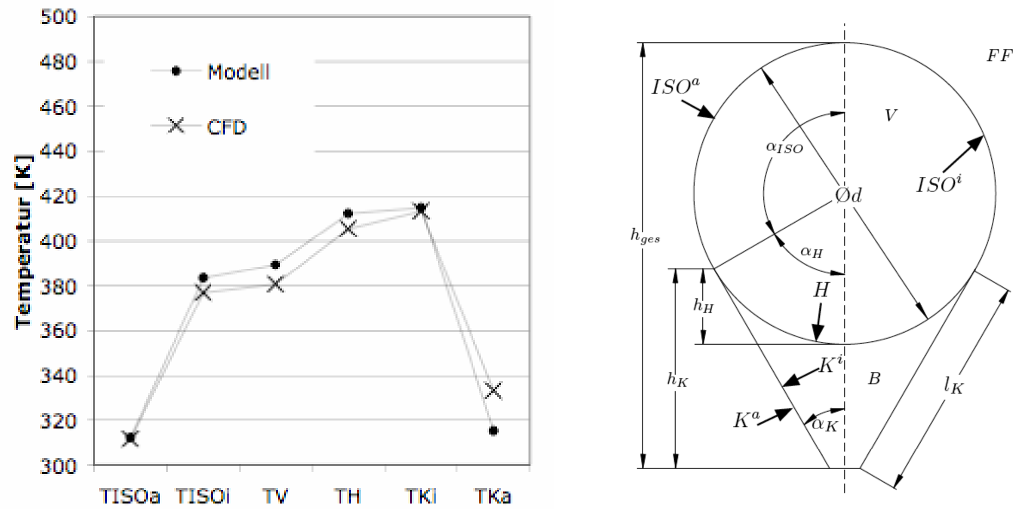

Figure 5: Comparison between temperatures derived from the low parametric model and CFD calculations.

Based on this model and some further CFD calculations the new design for the second prototype the HeiDAS UH was made. This 6.8 cubic meter balloon tall was build, tested and flown in over 30 successful test flights gaining useful data and proving the new material concept.

Figure 6 shows a representative test flight of the HeiDAS UH 6.8 m³ balloon. Warming up the envelope is necessary in order to avoid condensation. In order to avoid prickle the gas bag was prefilled with air. This air was replaced after the warming up phase when filling with steam of 150°C. After 20 minutes the filing was completed and the steam generator was disconnected from the balloon. Now a total lift of more than 50 N was reached which equals a specific lift rate of 0.75 kg/m³. The highest temperatures are measured at the so-called heat exchanger WT. From the south pole upwards the sensors WT1…4 are showing values of 270°C to 200°C. While the steam temperature GZ0 ranges between 140°C and 160°C the sensors at the surface deliver temperatures of 10°C to 20°C lower. The average propane consumption for this model was about 0.4 grams per second equaling some 18 kW of thermal power.

After flights the steam was released and the gasbag was refilled with dry air. This careful treatment was necessary since the given test balloon was made of the thinnest films available and seemed to be not really resistant against impacts such as prickle. Later test have shown, that even unreinforced polyimide film can be folded and

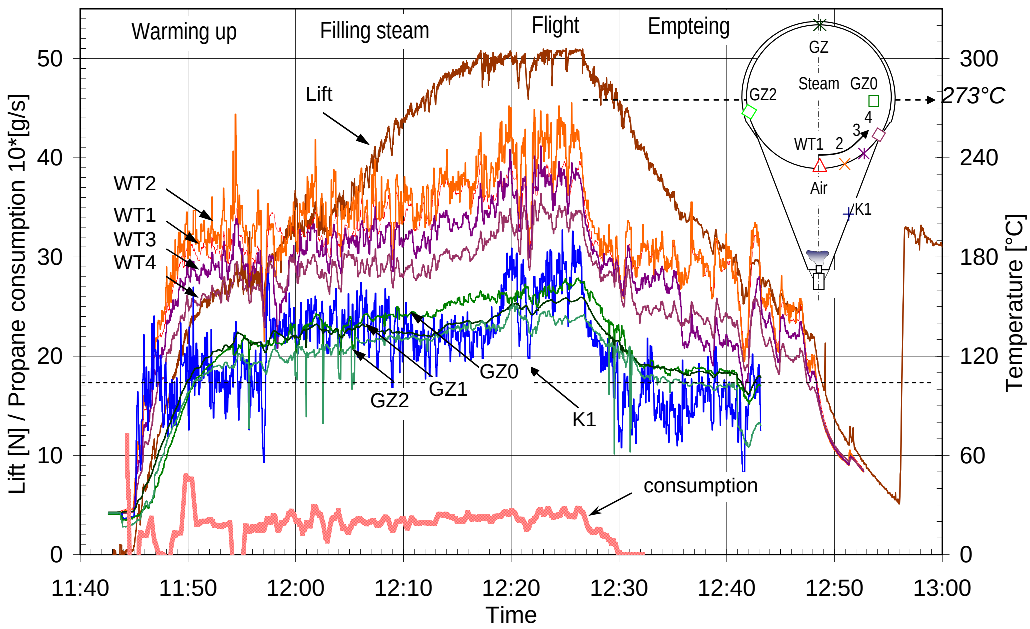

Figure 6: Data record of a test flight.

unfolded several hundreds of times without getting permeable for steam to much.

IV. Comparison of Performances

Conventional hot-air balloons generate buoyancies of 0.275 kg/m^3. Concerning the HeiDAS UH the buoyancy measured, relative to gas volume, is 0.735 kg/m^3. As such, the HeiDAS UH-steam balloon yields a lifting capacity of 2.5 times the lifting capacity of a same-size hot-air balloon and three quarters the lifting capacity of a same-size helium balloon. While the costs for the buoyant gas for the HeiDAS UH are considerably lower, the effort for insulation and envelope is higher. Compared to a helium balloon – once filled with the rare-gas, it stays in operation as long as possible –, hot-air balloons as well as the HeiDAS UH can be set up and broken down more quickly allowing for increased flexibly.

Temperatures in °C	HeiDAS UH	HeiDAS 2003	Hot-air balloon
Maximum envelope	260	160	120
Average gas	150	110	90
Average envelope inside	140	100	50
Average envelope outside	80	45	50
Ambient	23	23	10

Table 1: Comparison between temperatures at steam aerostats and regular hot-air-balloons.

Table 1 demonstrates the difference in temperature levels between steam aerostats and regular hot-air balloons. What becomes obvious too is the tremendous progress made concerning the 2nd generation HeiDAS, the HeiDAS UH. Increased temperature levels with the HeiDAS UH allow for reduced insulation strength from formerly 23 to now 7.5 mm. It would be possible to reduce insulation even further; however, this would come at the cost of higher fuel use. Thanks to its insulation and despite higher temperature levels, HeiDAS consumes about 1.0 kg of propane gas per hour – which is less than the fuel consumed by a hot-air balloon of equal take-off-weight. In case longer cruising times are required, fuel consumption could be reduced even more by increasing up insulation; however this also would drive up dead weight.

V. Outlook

Due to the novelty and complexity involved with hot-steam aerostats, developmental efforts were undertaken across a number of disciplines. The potential for increased buoyancy, reduced fuel consumption, and testing of new materials and calculation methods, however, reaches far beyond the academic realm. The development of HeiDAS UH, as the second prototype, has been proven successful throughout various test cruises. An extensive laboratory testing phase has just been concluded in fall 2005. Upon that, HeiDAS UH went for its first remote-controlled and independent cruise inside the Peter Behrens hall in Berlin in November 2005. At this point, an automated cruise control is under development for use on the prototype – it will also allow for steering and testing of larger balloons.

Before steam-balloons and steam-airships might pick up more regular tasks, however, more work needs to be done in terms of detail development and optimization. In any case, applied steam technologies may open up completely novel perspectives for lighter-than-air aviation.

After the projects upside-down twin, gas balloon, UNICEF-flyer, pneumatic gas balloon and pneumatic hot-air balloon basket, hot air airship, airfish and b-IONIC airfish, HeiDAS UH is another innovation developed for lighter-than-air aviation under Festo “Air in Air”. Across both, the domain of event marketing as well as its core expertise in pneumatic and electric actuators, once again, Festo is presenting itself as an industry leader in industrial automation.

References

[1]Bormann, A., Hermann, J. P., and Skutnik, S., "Alternative Buoyancy Concepts: First Numerical an Experimental Results from a Hot Steam Balloon (HeiDAS)," *3rd Annual Aviation Technology, Integration and Operations (ATIO)*, AIAA, Washington, DC, 2003.

[2]Bormann, A., Skutnik, S., and Staufer, M., "HeiDAS – Numerische Simulationen zur thermischen Performance von Rozìeren-Bauformen," *DGLR Workshop VII: "Flugsysteme leichter als Luft"*, 2004.

[3]Staufer, M., and Skutnik, S.., "HEIDAS Simulation der Strömungsverhäktnisse innerhalb eines Heißdampfaerostaten," Technische Universität Berlin, Berlin, 2003 (unpublished).

[4]Bormann, A., and Skutnik, S., "HeiDAS – Messungen am Heißdampfaerostaten zur Validierung numerischer Simulationen," *DGLR Workshop VII: "Flugsysteme leichter als Luft"*, 2004.

[5]Skutnik, S., "Niederparametrisches Ersatzmodell der Wärmebilanzen eines Heißdampfaerostaten gestützt auf Strömungssimulation und Messung," Diploma Thesis, Aeronautics and Astronautics Dept.,Technische Universität Berlin, Berlin, 2005.

[6]Skutnik, S., and Bormann, A., "Niederparametrisches Ersatzmodell der Wärmebilanzen eines Heißdampfaerostaten gestützt auf Strömungssimulation und Messung," *Deutscher Luf-t und Raumfahrtkongress*, 2005.