Alternative Buoyancy Concepts: First Numerical and Experimental Results from a Hot Steam Balloon (HeiDAS)

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ABSTRACT

HeiDAS is an abbreviation of the German expression of hot steam aerostat. The idea was to investigate the feasibility of superheated steam as a lifting gas. In a team effort young engineers and scientists developed a remote controlled hot steam balloon. Innovative materials and advanced calculation methods have been applied. The conduction, convection, and radiation were numerically simulated in order to choose a feasible balloon design and achieve the proper parameters both for a new developed flock-film-insulation and the necessary temperatures at the heat exchanger. After the first successful test and measurements it can be considered as the first insulated, steam balloon, which ever took off. This paper gives a survey of the design process and presents promising results from first numerical simulations and measurements.

INTRODUCTION

The vector-thrust airship “Luftffisch No.1” was filled with helium and after every flight the expensive lifting gas had to be released [*]. Searching for solutions cheaper than helium and more effective than hot air the idea of using steam came up. Steam as a lifting gas for airships has been proposed for almost two centuries [†]. Although the theoretical feasibility is obvious, severe practical questions have to be solved before steam can be considered to be a competitive and readily available lifting gas. Which light weight materials can sustain the corrosiveness and aggressiveness of hot steam? How can the filling and release be effected under usual weather conditions? What type of steam generator is available for filling and how will the lift gas be kept hot during the flight? How does the insulation affect buoyancy and control?

The challenge for the HeiDAS team was to design a small, fully functional prototype, which demonstrates the essential features and problems of the exceptional technology and allow systematic tests, measurements and modifications.

Fig. 1: HeiDAS at the test field of the Berlin University of Technology.

WATER VAPOUR

Water vapour with its small molecule weight of 18g/mol turns out to be an efficient, non-flammable lifting gas. With the energy content of only one kilogram propane approximately 15 kg of water can be vaporised. This quantity of steam fills a volume of $25\ m^3$ and can lift approximately 15 kg.

What makes steam an interesting alternative to existing gases? Steam doubles the lifting capacity of hot air. It is rather cheap in generation and non-flammable and non-toxic.

On the other hand steam extraordinarily causes corrosion and has high permeation. Condensate at the envelope leads to additional weight and has to be evaporated if necessary.

The mentioned factors have a restricting influence on the design and operation of a steam LTA vehicle. To avoid *condensation* pure steam has to be superheated in the whole gas bag. This requires a proper insulation. With a moderate admixture of air or other gases, condensation does not appear, even at lower temperatures [‡]. The high *corrosivity* of steam demands a careful selection of suitable materials for the entire system. The steam generator should be supplied with purified, de-ionised water. The high *permeation* of steam requires specific qualities of the polymer membrane.

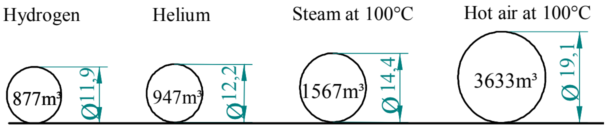

Fig. 2: Comparison of required volumes and diameters of spheres with a lifting capacity of 1000 kg.

HYDROGEN-OXYGEN STEAM GENERATOR

Even though process steam can be found in numerous facilities, the availability as a lifting gas is still not granted. Electrical steam generators have high power consumptions, oil-fired boilers often generate more steam than necessary, and they are not suitable for indoor testing. The superheating requires even extra devices.

Thus rather advanced steam generators were chosen for the small scale experimental rig. The stochiometric combustion of gaseous hydrogen and oxygen generates superheated steam of 3000 °C. Under supply of treated cooling water pure steam can be provided at a wide range of pressure and temperature very quickly.

The two "Hydronic" steam generators work with a total thermal power of 30 kW. The filling of the 29 m³ spherical bag takes half an hour. Due to the low power requirement, field generation of steam is possible.

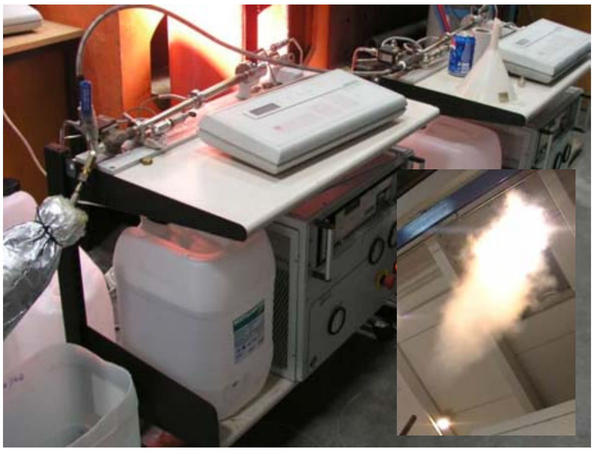

Fig. 3: Hydronic 2x15kW H2/O2 Steam Generator in the parallel mode. Exhaust of superheated steam.

ENVELOPE MATERIALS

The steam tightness and resistance of the materials used as well as their resistance against high temperatures play a key role. Usually polymers are decomposing sooner or later under application of superheated steam. This applies even to advanced polymers, which are in particularly resistant to hydrolysis. Dehydrogenation at high temperatures is one of the last manufacturing steps. This is reversed by the simultaneous impact of high temperatures and water vapour - the material degrades. The manufacturers do not recommend the usage of glass -, carbon- or aramid fibres for use under hot steam.

Conventional rib-stop nylon is an approved material for aeronautical applications such as hot-air balloons and paragliders. Because silicone coated rib-stop nylon was readily available it was chosen for the initial design. A silicone coated envelope, should resist steam up to 120 °C, however the first tests revealed certain insufficiencies. At temperatures above 120°C the silicone should be replaced by Ethylene Propylene Diene Monomer (EPDM).

However the favourite envelope material should be made from Poly Ether Ether Keton (PEEK), which has most of the required qualities. This innovative high-tech polymer is quite new on the market. PEEK is suitable for the envelope of a steam balloon as well as for films of a flexible heat exchanger. In order to provide additional tear strength, PEEK may be used in laminates or as finely woven fabric. Unfortunately neither of them is available and even the film comes at a dear price.

	Fabric	Coating	Film
Heat resistant	Polyamid (PA)<200°C	Silicone <210°C, EPDM <150°C	Mylar® ≈ 150°C Kapton®< 400°C PEEK® ≈ 240°C
Steam resistant	PA - No	Silicone <120°C EPDM <150°C	Kapton® - Not recommended PEEK® - Yes
Impermeable	No	Yes	Yes

Tab.1: Classification of envelope materials with respect to the major requirements for steam applications (Allowable temperatures according to manufacturer's specifications).

INSULATION

Insulation becomes an important issue, since avoiding condensation directly reduces weight. Even from the mere energy balance it was shown, that a certain quantity of lightweight insulation can save overall weight, because less fuel has to be consumed. This applies especially to longer flight durations [‡].

Fig. 4: Super-Insulating-Flock-Film (SIFD).

Conventional thermal LTA are using convection blockers in order to increase the insulating effect of the boundary layer. Such measures inside a steam balloon would lead to extra condensation.

Therefore AeroSIFD a new, reflective, ultra-lightweight flock insulator was developed and applied to the first steam balloon [‡, §]. AeroSIFD comes with a density of 8.5 kg/m³ and a measured thermal conductivity at 60°C of about 0.03 W/mK. Especially a good reflectivity pays well, since radiation heat transfer is dominant and increases by four to the power of temperature.

BALLOON DESIGNS

Implementing the Rozière principle the steam balloon is insulated additionally by a more or less wide air gap (Fig. 5, right). Then the inner gas bag is entirely surrounded by an outer volume of hot air. For the small prototype, the insulation thickness remains variable and the outer envelope is optional. Thus different designs with various boundary conditions can be investigated and the results compared with numerical simulations.

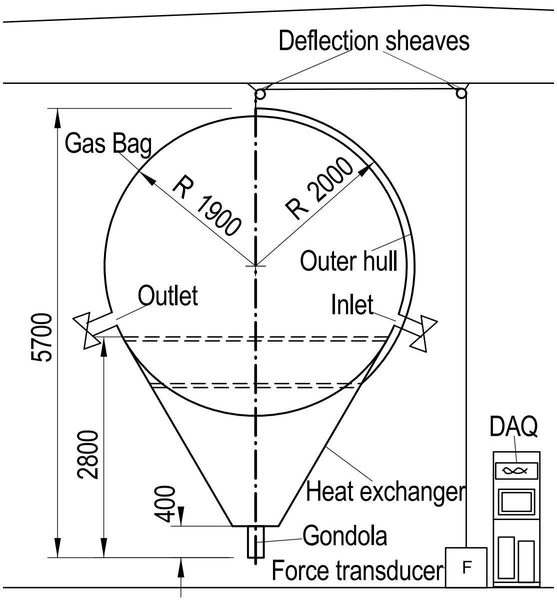

Fig. 5: Balloon designs and the test rig. Two designated types of Rozière: Half-Rozière (left) and Full-Rozière (right).

Fig. 5 illustrates the balloon design and the test rig in the laboratory at the Institute of Aeronautics and Astronautics at the University of Technology Berlin. The initial design of the hot steam balloon (HeiDAS) consists of a spherical, insulated gas bag and an insulated conical heat exchanger. We call it a Half-Rozière (Fig. 5, left).

The gas bag was made of silicon coated rib-stop nylon and was bonded tightly together with silicone adhesive. The insulation in the initial state consists of five layers of 3 mm AeroSIFD with a characteristic thickness of 15 mm.

The gondola carries burners, fuel and the control unit.

A flexible composition allows the quick implementation of modifications both for the insulator, the burner and the heat exchanger.

The basic design parameters of the balloon were derived from semi-analytical models [‡]. But the efficiency of the insulation and heat transfer and the interference of thermal conduction, convection and radiation are too complex to be described by an analytical approach. Therefore computational fluid dynamic (CFD) calculations have been carried out.

NUMERICAL SIMULATIONS

Numerical simulations were carried out with rotational symmetric 2D models first of a spherical gasbag and later of entire balloons including the far field. Additionally a 3D model of the gasbag was investigated.

The free convection is characterised by a Rayleigh-number:

$$Ra = \frac{\beta g}{a \nu} \Delta T \, l^3 = 1.431 \cdot 10^{11}$$

with
β thermal Expansion coefficient;
g gravitation constant;
a thermal conductivity;
ν kinematic viscosity.

Since free flow becomes turbulent with Rayleigh-numbers above $Ra=10^9$ calculations must consider turbulence and turbulence model has a strong impact on the results. First the RNG-k-ε-Model of Fluent was chosen. It is suited to treat flow of low Reynolds numbers, as it occurs in our case.

The rotational symmetric 2D model of the gasbag allowed changes in the boundary conditions of heating temperature and insulation. One aim was to find a design with condensate free operation. From the computations we determined the necessary thickness of insulation for given temperatures at the heat exchanger.

Fig. 6 is a chart showing condensing and non-condensing regimes of heating temperature and insulation. At the boundary between the two coloured fields the minimal temperature on the wall surface measures just 100°C. For the design point the maximum temperature at the heat exchanger was chosen to be 140°C. Accordingly insulation with a characteristic thickness of 15 mm is required. Higher temperatures at the heat exchanger allow a significant decrease of insulation.

For a better understanding - The characteristic insulation thickness refers to the minimal thickness. During the first tests, insulation was applied as entire panels across the upper pole. Thus a characteristic thickness of 15 mm was achieved at the equator with five layers, while at the pole a thickness of 90 mm prevailed.

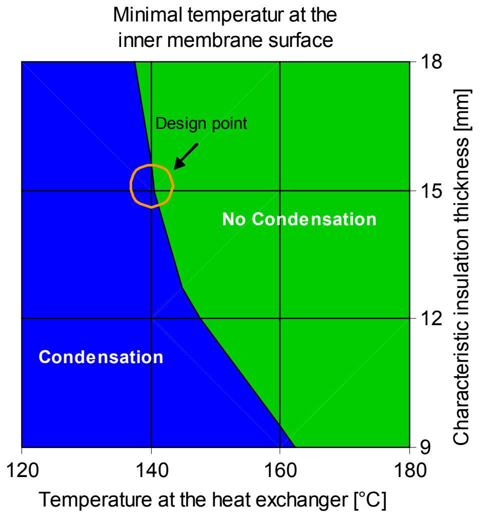

Fig. 6: Calculated minimal temperature at the wall surface of a steam balloon as a function of the boundary temperature of the heat exchanger and the characteristic thickness of the insulation.

Further calculations with constant insulation thickness resulted in a design point at 140°C and 18mm.

Fig. 7 shows the velocity vectors and the contours of temperature. At the transition of heating and insulation the ascending warm steam meets the descending, slightly colder steam. Two separate circulations are formed in each half of the balloon, which are not optimal for heat exchange. Consequently about 80 percent of the total heat flux is of radiative nature. Free convection with small velocity values below 0.5 m/s and nearly constant temperatures prevail inside the balloon.

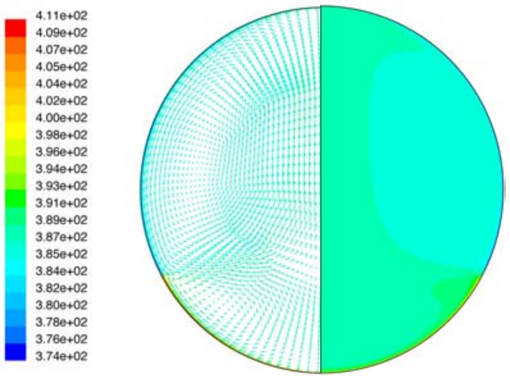

Fig. 7: Velocity vectors and contours of temperature inside the heated steam bag (Temperature of heating 140°C, characteristic insulation thickness 15mm).

The reliability of calculations strongly depends both on properly chosen physical methods and well defined boundary conditions. The boundary conditions for the sphere, as there is the temperature distribution of the heating and around the balloon were derived later by experiment.

The following calculations of the entire system with the gas bag, heat exchanger, burner and the far field allow a qualitative analysis of the two possible types of Rozièrs shown in Fig. 5. The burner provides 12.3 kW of heat, as it was measured in the steady state during the tests. Since the test burner is equipped with a fan, the flow in the reference cross-section must be accordingly. The boundaries of the far field are assumed to be isotherm.

As shown in Fig. 8 the flow inside the Half-Rozière remains almost the same as observed in the simplified model of Fig. 7. Even the comparison with the flow inside the Full-Rozière leads to an equal picture. Again two vertically separated zones of circulation appear which do not allow the warmed up steam flow to lift up along the inner wall of the gas bag. These pictures illustrate a rule of free convection: Flows go down with the gravity if heat is emitted. If heat is submitted to the flow the velocity vectors orientate themselves contrarily to the gravity, the flow goes upwards.

Fig. 8 deserves even closer attention. If the points of separation describe where the heating ends and the insulation starts one may conclude that the Full-Rozière with an air gap of 0.1 m does not significantly increase the heated surface at the gas bag, but it provides some extra insulation. Thus the Full-Rozière achieves higher lift and higher temperatures with the same heating power. If this gain of lift compensates the extra weight of the second envelope must be discussed separately. A further significant increase of lift can be provided by making the inside of the outer envelope reflective. This design is called Full-Rozière+ (Table 2).

Even though the computed temperatures are below 373.15 Kelvin no condensation appears in the numerical model and the steam remains gaseous. This simplification is allowed, since the desired result should not have condensation inside the gas bag. Due to the numerical results, operation without condensation is achieved by a Full-Rozière+ with 9 mm insulation or a Half-Rozière with twice as much. If the specific weight of 9 mm of insulation (76 g/m²) exceeds the equivalent value of the outer envelope a Full-Rozière+ can be considered more efficient.

Burner: 12.3 kW Insulation: 9mm	Half-Rozière	Full-Rozière	Full-Rozière+
Avg. Temp. [K]	354	365	389
Max. Temp. [K]	353	416	427
Min. Temp. [K]	345	356	381
Total Lift [N]	179	189	201

Table 2: Computed minimum and maximum temperatures at the inner wall surface of the gas bag, average temperature of steam and total lift from different balloon designs.

The extended model allows also calculating the temperature distribution at the boundary between the gas bag and the cone. As one can derive from Fig. 8, the temperature values decrease towards the upper cone ends. This was confirmed by later experiments.

The first results of the 3D analysis are summarised briefly. They are in good agreement with the 2D results. The same boundary conditions lead to equal average temperatures inside the balloon even with out having rotational symmetry. For the flow no steady solution could be found. Now there are more or less chaotic local up and down streams, the share of convective heat transfer in comparison to radiation increased slightly.

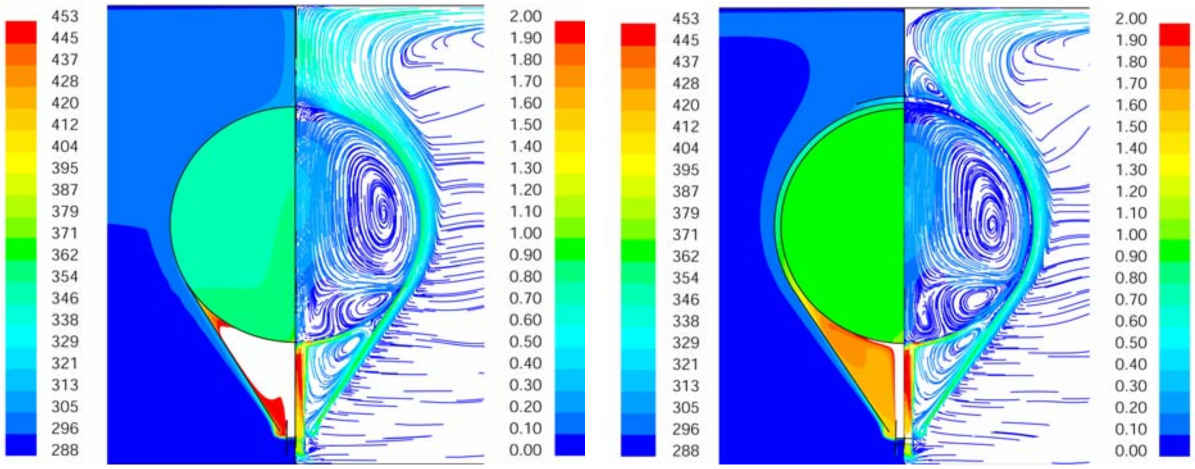

Fig. 8: Contours of absolute temperature [K](left half) and path lines coloured by velocity magnitude [m/s] (right half) of a Half-Rozière (left) and a Full-Rozière (right), (Fluent6.1, RNG-k-ε, unsteady).

TEST AND FLIGHT EXPERIENCE

The entire performance of the balloon as well as the filling procedure was investigated. At the contact with colder material steam will condense immediately. Consequently the entire balloon including the insulation and the filling tubes have to be preheated if condensation is not desired.

Two ways of filling can be classified; the displacement fill-up and the closed fill-up. Closed fill-up means, that only steam is injected into an evacuated gas bag. This requires special precaution, proper preheating and a sophisticated design and control of the steam inlet.

After some attempts, the displacement filling succeeded even with only one of the two steam generators. Therefore the balloon was filled entirely with air and heated with the burner until a temperature above 100°C was achieved inside the gas bag. Now superheated steam with up to 300°C was injected into the balloon, until it reached sufficient buoyancy for take off. After disconnecting the steam supply, sufficient lift could be provided at least for a quarter of an hour. After lifting the ballast weights, the balloon took of, and moved smoothly towards the ceiling.

During the first tests the changes in buoyant force and characteristic temperatures inside the gas bag and the heat exchanger were measured.

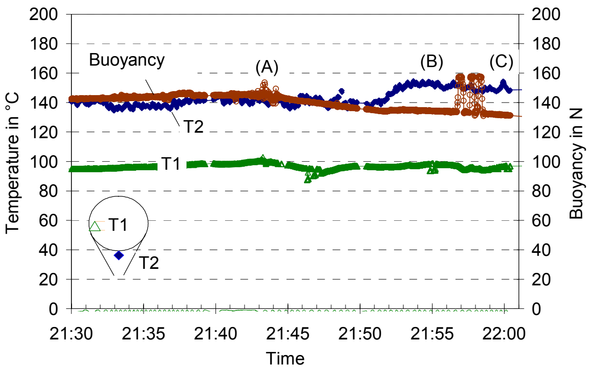

Fig. 9: Measured temperatures inside the balloon (T1) and at the heating (T2) and reduced buoyancy during the first take off on May 7th 2003.

The flight time in the current state was mainly limited due to permeation of steam through the envelope. During nearly two hours of testing more than three kilograms (33N) of steam disappeared out of the gas bag and condensed at the insulation. With this extra weight the effective buoyancy was reduced. On the other hand this extra weight must be added to the measured maximum lift of 145N. Consequently a total lift of about 178 N was achieved - only 7 per cent less than the prospected lift of 190 N. One may further conclude that the inside of the gas bag must have remained almost free of condensate, which altogether confirms the superb qualities of the insulation. Anyhow the insufficiencies of the silicone coated rib-stop nylon became obvious.

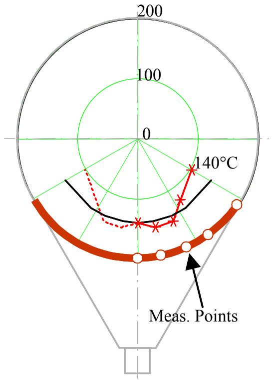

Fig. 10: Measured temperature distribution.

At a central temperature of 140°C towards the upper cone ends the measured values are coming close to 100°C (Fig. 10). The temperature inside the balloon was measured at the same latitude as the inlet vent with an offset in circumferential direction of one meter. In this region the lowest wall temperatures where calculated. Thus in a 10 mm distance from the wall surface a temperature of almost 100°C was measured, half meter towards the balloon centre temperatures reached about 110°C.

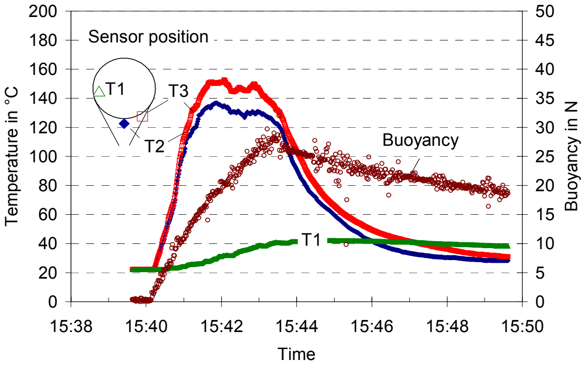

Fig. 11: Time history of gas temperatures T and buoyancy of an insulated balloon during a temperature input of ΔT = 120°C.

The impact of changes in temperature of the heat exchanger was investigated when the balloon was filled entirely with air. As expected, due to the insulation the changes in temperature inside the gasbag are very slow. Especially the decrease of buoyancy after switching off the burner is rather small. In order to provide more thermal control the highest possible temperature at the heat exchanger is required. Additional systems of buoyancy control may be considered, such as controllable outlet valves for the hot air currents or extra ballasting.

CONCLUSIONS

A small, insulated steam balloon, filled with steam took off for the very first time, reaching almost 180 N lift with a steam volume of nearly 29 m³. With full steam supply, short outdoor flights are possible.

Superheating and insulating of a steam balloon were implemented successfully.

First tests and measurements are in fair agreement with the analytical and numerical predictions.

Further numerical simulations showed that a Half-Rozière needs two times more insulation than a Full-Rozière to make operation without condensation possible.

The computer simulations should be continued and validated with further experimental results. Therefore the flexible test rig is suited to provide the data needed.

In order to allow higher temperatures at the heat exchanger and to avoid permeation more advanced materials like EPDM coated fabric or PEEK® should be chosen for the envelope and the heat exchanger respectively.

The useful experiences both from experiments and calculation, makes a manned flight in a steam balloon come to closer reach.

ACKNOWLEDGEMENT

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Fig. 12: Sequence during the first take off. After lifting the ballast weights, the balloon took of, and moved smoothly towards the ceiling.