Design of a 1.5 Seconds High Quality Microgravity Drop Tower Facility

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(Received July 31st, 2015)

In collaboration with the Institute of Space Systems at the University of Stuttgart, a new non-vacuum drop tower facility shall be built at the Center for Astrophysics, Space Physics and Engineering Research at Baylor University with design parameters of at least 1.5 seconds drop duration while providing a quality of microgravity of at least $10^{-5} g$. A dual drop capsule design was optimized under an aerodynamic perspective to deliver this quality of microgravity, which has so far only been possible at resource intensive vacuum drop towers.

Key Words: Microgravity Research, Drop Tower Design, Aerodynamic Optimization, CFD

Nomenclature

- $a$: Acceleration
- $c$: Reference Length
- $C_d$: Drag Coefficient
- $d$: Diameter
- $F$: Force
- $g$: Gravitational Acceleration
- $h$: Height
- $m$: Mass
- $Ma$: Mach Number
- $k$: Turbulent Kinetic Energy
- $p$: Pressure
- $Re$: Reynolds Number
- $S$: Reference Area
- $s$: Distance
- $t$: Time
- $v$: Velocity
- $y^*$: Dimensionless Wall Distance
- $\mu g$: Quality of Microgravity
- $\nu_t$: Turbulent Kinematic Viscosity
- $\omega$: Dissipation Frequency

Subscripts

- $b$: Bottom Wall of the Capsule
- $f$: Fairing of the Outer Capsule
- IC: Inner Capsule
- OC: Outer Capsule
- rel: Relative Motion between IC and OC
- s: Side Wall of the Capsule
- t: Top Wall of the Capsules

1. Introduction

Microgravity is the condition of a body in free fall without any external forces acting on it. This results in a stress and strain free state, in which fluids show an altered behavior, making microgravity experiments essential for research in space science, but also valuable for research in biology, fluid mechanics, combustion and material science.

Since a free falling body cannot accelerate without any external force acting on it, this may be used to quantify the quality of the microgravity environment. This is generally measured in fractions of the gravitational acceleration $g$, quantifying the difference in the current acceleration of a falling body to $g$. Research has shown that a quality of microgravity of $\mu g \leq 10^{-5} g$ satisfies the requirements of most microgravity experiments.\(^2\) Drop towers have the advantage that they can deliver this quality of microgravity combined with adequate payload masses and virtually unlimited repeatability under same experiment conditions, at comparably low costs.

In a collaboration between the Institute of Space Systems (IRS) at the University of Stuttgart, a new non vacuum drop tower facility shall be built at the Center for Astrophysics, Space Physics and Engineering Research (CASPER) at Baylor University with the design parameters of:

- a drop duration of at least 1.5 seconds,
- a quality of microgravity of at least $10^{-5} g$,
- a payload capacity of up to 160 kg, and
- maximum experiment dimensions of:
  - $\emptyset$ 600 mm x 950 mm.

This quality of microgravity has to date largely been achieved at drop towers in which the capsule containing the experiment drops inside a vacuum chamber such as the drop tower at ZARM, Bremen, Germany or the Zero Gravity Research Facility at NASA Glenn Research Center, Cleveland, USA.\(^2\) However, such vacuum drop towers are resource intensive and only few drops per day can be realized due to the need of evacuating the drop chamber before every drop. In order to achieve this quality of microgravity over the entire drop duration in atmosphere, a dual capsule design was designed and optimized to realize the required $\mu g$. Although this dual capsule design is currently being used at multiple drop towers for example the Microgravity Drop Tower at Queensland University of Technology (QUT), Brisbane, Australia or the 2.2 Second Drop Tower at NASA
Glenn Research Center, Cleveland, USA, these towers only report a $\mu g \leq 10^{-4}g$ and $\mu g \leq 10^{-3}g$ respectively. This paper presents the general drop tower layout, while focusing on the aerodynamic optimization of the dual capsule design with the aid of computational fluid dynamics simulations and experiments. Previous work demonstrating the general layout and preliminary results was presented in 6).

2. Drop Tower Layout

The proposed drop tower facility will be located inside the atrium of the Baylor Research and Innovation Collaborative (BRIC) extending over four floors (17.1 m) to ensure maximum available drop height and duration. Figure 1 shows an isometric view of the drop tower and its main components: the drop capsules, the release mechanism, the drop shaft, the winch and the deceleration device.

The drop capsule consists of an inner capsule containing the experiment and an outer capsule acting as a drag shield to protect the inner capsule from aerodynamic drag which can lead to a low quality of microgravity. An in depth description of the capsule design follows in section 3. Depending on customer demand, experiments will be installed into the inner capsule either at their own facility or directly on-site. The experiment’s functionality will be tested, followed by a balancing of the inner capsule. Once the inner capsule is connected to the release mechanism it will be placed inside the outer capsule. The integrated system will then be moved from the Space Science Laboratory’s integration room into the atrium where the capsule will be connected to and raised by the winch. For reasons of safety the drop zone will be enveloped by a drop shaft consisting of a cable net, which will be mounted to the ground on the first floor and the mounting structure at the top of the tower.

After the deceleration mechanism is placed into the bottom of the drop shaft and the capsules have stopped moving, they will be released. Release occurs smoothly causing minimal vibration in the inner capsule. The deceleration device is designed to decelerate the capsules at the end of the drop from their maximum velocity of approximately 16 m/s to 0 m/s with deceleration not exceeding 40 g. After the drop, the capsules and the deceleration device will be moved into the laboratory again where they can be prepared for another drop. Once fully operational, the drop tower should be capable of up to 10 drops per day.

3. Aerodynamic Drop Capsule Design

3.1. Basic capsule design

The general capsule design, as it has for example been realized at the Queensland University drop tower (QUT), is displayed in Fig. 2. At the start of the drop the capsules are both at rest. During the drop the inner capsule (IC), containing the experiment, is protected from aerodynamic drag by the outer capsule (OC), which acts as a drag shield. Since neither capsule is attached to the other and the OC experiences aerodynamic drag, relative motion of the bottom of the OC towards the bottom of the IC will be observed. The velocity of this relative motion shall be referred to as $v_{rel}$ and the relative acceleration as $a_{rel}$. This shows that even though the IC is protected from the main aerodynamic drag it will still experiences a force, created by the air inside the OC flowing around the IC due to the relative motion of the OC towards the IC. Minimizing this force is the primary goal of the capsule design optimization procedure described below.
3.2. Optimization approach

The force on the IC can be minimized by minimizing the relative motion between the capsules. For reasons of simplicity all equations shall be expressed in a coordinate system located at the top of the tower pointing vertically downwards.

The OC experiences two main forces acting on it: The gravitational force \( F_g \) and the drag force \( F_d \), which can be stated for an OC with mass \( m \), drag coefficient \( C_d \), reference area \( S \) and velocity \( v \) appearing under the air density \( \rho \) as:

\[
F_g = m \cdot g \tag{1}
\]

\[
F_d = \frac{1}{2} C_d \cdot \rho \cdot S \cdot v^2 \tag{2}
\]

These forces act in opposite direction so the law of conservation of momentum states:

\[
m_{oc} \cdot a_{oc} = F_{g,oc} - F_{d,oc} \Rightarrow a_{oc} = g - \frac{1}{2} \frac{C_d}{m_{oc}} \cdot \rho \cdot S_{oc} \cdot v_{oc}^2 \tag{3}\]

Like the OC, the IC experiences both the gravitational force and an aerodynamic force. However, since the \( \mu g \) within the IC shall be \( \leq 10^{-5} g \), the impact of this force is negligible on the motion of the IC:

\[
a_{ic} = g - 10^{-5} g \Rightarrow a_{ic} \approx g \tag{4}\]

The relative acceleration of the OC towards the IC follows by subtracting the acceleration of the OC (Eq. (3)) from the IC (Eq. (4)):

\[
a_{rel} = a_{ic} - a_{oc} \Rightarrow a_{rel} = \frac{1}{2} \frac{C_d}{m_{oc}} \cdot \rho \cdot S_{oc} \cdot v_{oc}^2 \tag{5}\]

Eq. (5) provides the parameters which can be varied to minimize the relative motion between the capsules. Decreasing \( a_{rel} \) can be realized by increasing \( m_{oc} \) and decreasing \( C_d \cdot \rho \cdot S_{oc} \). However, it is important to note that \( S_{oc} \) is not independent from the dimensions of the IC. In Fig. 3 it can be seen that \( S_{oc} \) depends on the diameter of the IC \( d_{ic} \) and the radial distance between the IC and OC sidewalls \( s_r \). If \( d_{ic} \) is only slightly larger than \( d_{ic} \), the relative velocity of the air between the capsule-walls increases, thus increasing friction and \( \mu g \). This shows that \( s_r \) is a parameter which must be optimized for a given \( d_{ic} \). Other parameters needing to be optimized independently of the previously stated parameters, are the vertical IC distances between the capsules at the beginning of the drop \( s_1 \) and \( s_2 \), as displayed in Fig. 3.

In addition to optimizing these parameters, creating a vacuum inside the OC is a further possible approach to this problem and is utilized at the National Microgravity Laboratory of the Chinese Academy of Sciences (NMLC), Beijing, China. However, the creation of a vacuum inside the OC before every drop substantially increases the dual capsule design complexity as well as the drop roll over time. This has been shown to be necessary for the CASPER drop tower due to the fact that maximum \( v_{oc} \) reached is of much lower magnitude than that seen at the taller NMLC drop tower (17.1 m vs. 116 m).

Calculating \( \mu g \) using the drag equation (Eq. (2)) for the IC fails due to the fact that this equation is only suitable for flow around bodies far away from other disturbing surfaces. Clearly an analytic approach works well in demonstrating the impact of the main OC parameters \( m_{oc} \), \( C_d \cdot \rho \cdot S_{oc} \) but fails to actually produce the \( \mu g \) for a given OC and IC design. This means that the force acting on the IC must be calculated using a computational fluid dynamics (CFD) simulation. However, simulating both capsules as well as their environment at the same time proved to be CPU intensive and impractical for two reasons: The computational domain is large and dynamic, requiring a motion solver for the capsules. Furthermore, multiple different configurations of parameters (around 80) needed to be simulated with different diameters for both capsules, different masses for the OC and different shapes for the OC.
Therefore, the hybrid approach displayed in Fig. 4 was chosen. Here the $C_{d,OC}$ of different OC shapes is evaluated with steady state CFD simulations (see section 3.3.). The calculated $C_{d,OC}$ is then used with $d_{OC}$, $s_x$ and $m_{OC}$ as the input for calculating the relative motion of the capsules analytically using Eq. (9), which is derived below. The actual force on the IC is then evaluated employing another CFD simulation and the analytic results as input where the computational domain only includes the inside volume of the OC. The flow field around the IC arises from the air being pushed up by the OC moving with the relative motion calculated previously. This approach effectively results in the same flow field that produces the aerodynamic force on the IC during a drop without having to simulate the flow field around the OC. This method does not require a motion solver (since the motion is predefined) and allows vast parameter changes since $C_{d,OC}$ is largely independent of the OC diameter $d_{OC} (= d_{IC} + 2 s_x)$. Thus, for one OC simulation, delivering a $C_{d,OC}$, many simulations of the relative capsule motion could be done for different $d_{IC}$, $s_x$, $s_y$ and $m_{OC}$. After the simulations were completed, wind tunnel tests were conducted using a scaled model of the OC to experimentally measure $C_{d,OC}$.

Furthermore, an original scale experiment, closely resembling the simulations in section 3.4., was done to empirically verify the results for the force acting on the IC. Experimentally verify the results for the force acting on the IC.

An analytic equation for $v_{rel}(t)$ can be derived under the assumption that $C_{d,OC}$ is constant during the drop. In this case Eq. (3) is a separable differential equation:

$$a_{OC} = \frac{dv_{OC}}{dt} = g - kv_{OC}^2$$

where

$$k = \text{const.} = \frac{1}{2 m_{OC}} C_{d,OC} \rho S_{OC}$$

$$S_{OC} = \frac{\pi}{4} (d_{IC} + 2 s_x)^2$$

Solving eq. 6 for $v_{OC}(t)$ leads to the time dependent velocity equation of the OC:

$$v_{OC}(t) = \sqrt{\frac{g}{k}} \tanh(\sqrt{gk} t)$$

It should be noted that in reality $C_{d,OC}$ is only constant for a constant $v_{OC}$. During the drop $v_{OC}$ ranges between 0 m/s and approximately 15 m/s, which introduces some uncertainty to the reliability of Eq. (8). The steady state simulations in section 3.3, were mostly done for $v_{OC} = 15$ m/s. However, to take the effect of a smaller $v_{OC}$ into account some simulations were done for different $v_{OC}$ and it was found that $C_{d,OC}$ was approximately 15% larger for a slower $v_{OC} = 2$ m/s. This is why a factor of 1.2 was multiplied to $C_{d,OC}$ in Eq. (7). Although some uncertainty remains this insures that the calculated $C_{d,OC}$ for $v_{OC} = 15$ m/s is at least not too small for the majority of the drop time, where $v_{OC} \geq 2$ m/s. With this factor, eq. 4 and eq. 8 $v_{rel}$ derives to be:

$$v_{rel}(t) = v_{IC}(t) - v_{OC}(t)$$

$$v_{rel}(t) = g t - \sqrt{\frac{2}{k}} \tanh(\sqrt{gk} t)$$

where

$$k = \frac{1.2}{8 m_{OC}} C_{d,OC} \rho \pi (d_{IC} + 2 s_x)^2$$

It is useful to notice that Eq. (9) demonstrates how $C_{d,OC}$ and $m_{OC}$ affect the relative motion between the capsules for given $d_{IC}$ and $s_x$: If in reality $C_{d,OC}$ will turn out to bigger than the value the following simulations produced, it can be counteracted by increasing $m_{OC}$ by the same amount, leading to the same relative motion as there would have been with the calculated $C_{d,OC}$. The goal of the OC design process was to find an economic OC design which delivers the required $\mu g$ in the simulations without further increasing of $m_{OC}$. However, increasing the OC mass is not a ruled-out option if in reality $C_{d,OC}$ will turn out to bigger than expected.

3.3. Determining $C_{d,OC}$ with CFD-simulations

All simulations in this work employed the open source CFD Toolbox OpenFOAM. With maximum relative air velocities (relative to the OC) during the drop at around $v_{OC} \approx 15$ m/s, and the speed of sound $a \approx 340$ m/s (international standard atmosphere at sea level) the maximum Mach number in the simulations is $Ma \approx 15/340 = 0.04$. This means that incompressible flow can be assumed with good accuracy for all simulations conducted. Additionally, since all simulations were axisymmetric they were simplified to quasi-two dimensional simulations, which drastically reduced calculation costs.

The steady state solver for incompressible, turbulent flow that is included in OpenFOAM and was used for the OC shape simulations is called simpleFOAM. As the name suggests it is based on the classic Semi-Implicit Method for Pressure Linked Equations (SIMPLE) algorithm, which links pressure and velocity on staggered grids using an iterative process and the incompressible Reynolds Averaged Navier Stokes (RANS) equations. To close the RANS equations a turbulence model needed to be chosen. The turbulence model used in these simulations is the Shear-Stress-Transport (SST) $k-\omega$ model. It was chosen due to its robust behavior close to walls and in free stream. Furthermore, it performs well in situations of flow separation, which occurred on top of the OC. This turbulence model is available under the name $kOmegaSST$ in OpenFOAM. With the parameters from the turbulence model, the list of flow variables includes the velocity vector $\mathbf{v} = (v_x, v_y, v_z)$, the pressure $p$, the turbulent kinetic energy $k$, the dissipation frequency $\omega$ and the turbulent kinematic viscosity $\nu_t$. The different boundaries considered in the simulation included the inlet, the capsule wall and the outlet as well as the symmetry planes resulting from the quasi-two dimensional simplification and the outer simulation boundary in radial distance. The latter two were given simply a slip boundary condition for all flow parameters, which restricts normal flow to the boundary and sets the gradient of the scalar flow parameters to zero. At the outlet, $p$ was set to zero (any value
is fine since only the relative pressure distribution around the capsule is required to calculate $C_{d,OC}$ with the gradient of all other parameters set to zero. For the inlet $v$ was set to $(0, 0, v_o = 15 \, m/s)$, the gradient of $p$ was set to zero and the turbulence parameters were assigned to be the recommended values for external aerodynamics simulations as described by Spalart and Rumsey in 12), where $c$ is the reference length ($c = h_{OC}$):

$$k_{inlet} \approx 1 \times 10^{-4} v_o^2$$
$$\omega_{inlet} \approx \frac{5v_o}{c}$$
$$v_{t,inlet} \approx 2 \times 10^{-5} v_o c$$

At the capsule wall, $v$ is set to $(0, 0, 0)$ and a logarithmic wall function was implemented by selecting the boundary conditions nutkWallFunction for $v_t$ and $kqWallFunction$ for $k$ in OpenFOAM.\textsuperscript{10) The boundary condition that was used for $\omega$ is based on the near wall treatment proposed by Menter in 13). In OpenFOAM this boundary condition is called omegaWallFunction.\textsuperscript{10) To calculate the force (thus $C_{d,OC}$) acting on the capsule the pressure and the shear stress need to be integrated over the capsule wall boundary. This can be done automatically in OpenFOAM with the internal tool forceCoeffs.\textsuperscript{10)}

As a first step, multiple simulations were done for different OC nose shapes: A half-spherical nose and two conical nose shapes with different angles. For the OC dimensions some preliminary assumptions were made since the actual values were defined by the simulations described in section 3.4. (Assumptions: $d_{OC} = 1 \, m$, $h_{OC} = 2 \, m$). The assumed values were shown to not be critical since changes of $d_{OC}$ and $h_{OC}$ of up to 20% only changed $C_{d,OC}$ around 1%. The resulting velocity field of these simulations are displayed in Fig. 5. In the case of the 45°-conical nose it can be clearly seen that there is a large boundary layer separation occurring after the nose. This leads to a wider area of flow separation which results in a rather bad drag coefficient of $C_{d,OC} = 0.46$. The boundary layer is not separating as strongly for the other two nose shapes, which results in better drag coefficients: $C_{d,OC} = 0.26$ for the 30°-conical and $C_{d,OC} = 0.20$ for the half-spherical nose shape, which is why this nose shape was chosen.

In a next step an aerodynamic fairing for the top of the OC was developed to further decrease the $C_{d,OC}$. Ideally, this fairing prevents the boundary layer from separating at the top of the capsule to decrease pressure drag. The fairing was designed with the shape of a truncated cone which can be seen in Fig. 6. Simulations were run for differing fairing angles $\alpha_f$ and fairing heights $h_f$ in order to make an educated design choice. An optimal $\alpha_f$ was found to be 16° with $h_f = 0.6 \, m$. This substantially improved $C_{d,OC}$ to 0.09.

3.4. Determining the Capsule Dimensions with CFD-Simulations

To simplify the following simulations the outside of the IC and the insides of the OC were assumed to be cylindrical (meaning the base frames were ignored). This resulted in the numerical setup displayed in Fig. 7. This simulation environment is axisymmetric, so it was once again decided to simplify this three dimensional environment to a quasi-two-dimensional environment in order to reduce computational costs. In these simulations a steady flow could not be assumed since the OC moves dynamically around the static IC. Although the flow is not steady but transient, incompressibility of the flow was assumed due to the fact that the total volume of air is constant and velocities were small ($v_{rel}(t) < 0.1 \, m/s$).

As for the simulations in section 3.3., the incompressible RANS approach was suitable with the SST $k$-$\omega$ model as the turbulence model. This turbulence model was especially interesting due to the ability of $k$-$\omega$ models to be applicable for near wall modeling (modeling without logarithmic wall functions). The modeling of the boundary layer with logarithmic wall functions showed to be unsuitable for these simulations due to the rather low values of $v_{rel}(t)$ which resulted in low Re-flow. When a near wall modeling approach is taken, the boundary layer is modeled all the way into the viscous sublayer at a much higher resolution, which means the dimensionless wall distance $y^+$ of the lowest cell layer is recommended to be around $y^+ = 1$.\textsuperscript{10) Whether $y^+$ was small enough could only be checked once the simulations were done, so achieving good boundary layer modeling was an iterative process. The standard OpenFOAM solver for incompressible, transient, turbulent flow with a dynamic mesh is the pimpleDyMFoam-solver.\textsuperscript{10) This solver is based on the PIMPLE-algorithm (merged PISO-SIMPLE) which combines
the SIMPLE algorithm with the common Pressure-Implicit with Splitting of Operators (PISO) algorithm. Furthermore, the “DyM” stands for its ability to work with dynamic environments. To create a dynamic motion of the mesh a specific solver needed to be assigned to handle the mesh motion. The velocityComponentLaplaciansolver was chosen, which basically moves the boundaries (in this case the OC and IC walls) with a velocity profile that needs to be predefined as a separate boundary condition for each boundary. Instead of recreating the mesh for every time step this solver “stretches” the mesh around the moving boundaries saving computational costs if the mesh motion is not too large.14) There are three different boundary conditions in this simulation. The OC wall, the IC wall and the symmetry planes. Like before the symmetry planes were given a slip boundary condition for all flow parameters. Both capsule walls have a no-slip boundary condition. So for those boundaries the boundary conditions for \( p \) and \( \mathbf{v} \) were equal to those of the OC in the simulations described in section 3.3. As mentioned before the motion of each boundary needed to be defined as well. This was \( (0, 0, 0) \) for the IC and \( (0, 0, v_{\text{rel}}(t)) \) for the OC with a \( 0 \leq t \leq 1.7 \) s. With the near wall modeling approach the OpenFOAM boundary condition types for low-Re modeling were used, namely the nutLowReWallFunction for \( v_1 \) (this sets \( v_1 \) to zero, resulting in no wall function) and kLowReWallFunction for \( k \) (which sets \( k \) to zero) at both capsule walls. The boundary condition used for \( \omega \) was the same as for the simulations described in section 3.3. The tool forceCoeffs was used again to measure the force acting on the IC over the drop duration. Dividing this force with the expected mass of the IC led to the \( \mu g \) in the following figures.

The parameters required as input for Eq. (9), the geometry of the simulations and the calculation of \( \mu g \) are listed below:

- \( m_{OC} \approx 160 \) kg (estimation)
- \( m_{IC} \approx 208 \) kg (estimation)
- \( C_{\text{ICOC}} = 0.09 \) (taken from the previous simulations)
- \( 0.55 \text{ m} \leq d_{IC} \leq 0.69 \text{ m} \)
- \( h_{IC} = 0.95 \text{ m} \)
- \( 0.08 \text{ m} \leq s_s \leq 0.18 \text{ m} \)
- \( 0.05 \text{ m} \leq s_b \leq 0.3 \text{ m} \)
- \( 0.01 \text{ m} \leq s_l \leq 0.16 \text{ m} \)
- \( 0 \leq t \leq 1.7 \) s (longest possible drop time)

Figure 8 shows the progression of \( \mu g \) during one simulation from \( t = 0 \) s to \( t = 1.7 \) s for \( d_{IC} = 0.6 \) m, \( s_s = 0.125 \) m, \( s_l = 0.1 \) m and \( s_b = 0.15 \) m. As explained earlier these results show that \( \mu g \) gets increasingly worse during the drop. The fact that the rate at which \( \mu g \) is increasing is also increasing over the drop demonstrates how hard it would be for this capsule design to deliver the required \( \mu g \) for higher drop durations.

Figure 9 shows the maximum occurring \( \mu g \) for a range of \( d_{IC} \) and \( s_s \) while \( s_l = 0.05 \) m and \( s_b = 0.5 \) m. Clearly, there is an optimal wall distance \( s_s \) for every \( d_{IC} \). The cause for this was explained earlier: If \( s_s \) is too small, the air has little space to pass between the capsules during relative motion, which increases its velocity and friction thus has a negative impact on \( \mu g \). On the other hand if \( s_s \) is too big \( d_{OC} \) is large too, resulting in larger magnitudes of \( v_{\text{rel}} \) which also has a negative impact on \( \mu g \). Figure 9 shows that the optimal \( s_s \) lies between 0.12 m and 0.14 m for \( 0.55 \text{ m} \leq d_{IC} \leq 0.69 \text{ m} \). Furthermore, Fig. 9 demonstrates that \( \mu g \) gets better the smaller \( d_{IC} \) is. After these simulations \( d_{IC} \) was decided to be 0.6 m with an optimal \( s_s = 0.125 \) m.

In Fig. 10 the maximum occurring \( \mu g \) was plotted for a constant \( d_{IC} = 0.6 \) m and \( s_s = 0.125 \) m and ranging \( s_l \) and \( s_b \). Figure 10b shows that \( s_b \) needed to be sufficiently large to deliver a good \( \mu g \). This is especially interesting considering that the relative motion of the OC towards the IC is only of about 2 cm. Clearly \( s_b \) needs to be much bigger than this.
value, which could be necessary due to a possible buildup of an air cushion under the IC at the end of the drop for \( s_b < 0.1 \) m. In Fig. 10a it was surprising to see how large the impact of \( s_b \) on \( \mu g \) is. One possible explanation for this effect is that small values of \( s_b \) result in rather fast flow of air to fill the gap between the top of the IC and the OC when the latter moves upwards. This fast flow causes the relative pressure to drop which results in a suction effect. After these simulations it was decided that \( s_b \) shall be 0.1 m and \( s_b = 0.15 \) m.

Clearly, with the parameter choices described above, \( \mu g \) satisfies the requirement of \( \mu g \leq 10^{-5} \) g. Of course these values would be different for different capsule masses. This is why it is important that these masses will be met for the actual capsules. An experiment lighter than the maximum payload will require the mass of the IC to be artificially increased so it is always of the same magnitude. Furthermore, as mentioned in section 3.2, \( m_{OC} \) might need to be increased artificially as well to counter the effect a \( C_{d,OC} > 0.09 \) would have.

3.5 Experiments

Once the final dimensions of the OC were determined using the simulations described in section 3.4, a 1:9 scale model of the OC was tested in the wind tunnel located inside the mechanical engineering department of Baylor University. The model was tested both with and without a fairing. Without the fairing the measured \( C_{d,OC} \) was around 0.30 and with the fairing it was around 0.24. Although, these tests verified that the fairing improved the aerodynamics of the OC, the values were much higher than in the simulations. This can probably be explained with the Reynolds number \( Re \) which should have been the same to ensure flow similarity for comparable results, but was approximately one order of magnitude too small for the wind tunnel tests (1.1×10^6 vs. 1.2×10^8). However, it is also possible that the simulations produced a too small value for \( C_{d,OC} \). The tests delivered a \( C_{d,OC} \) more than twice as big as the simulations produced. Therefore, for further development on the drop tower it will be required to assume a \( m_{OC} \) of more than twice of the previous value of 160 kg to deliver the required \( \mu g \).

The idea of the second experiment was to verify the basic simulations around the relative capsule motion and at the same time do some experimentation whether an aerodynamic cover (mainly a cylindrical cover) for the IC is beneficial for producing a \( \mu g \) environment or not. Figure 11 shows the basic setup of the experiment. The IC model was then attached to a rig that was resting on a scale. The OC model was attached to a stepper motor, which was controlled by a microcontroller and could pull up the OC with \( v_{rel}(t) \). Both capsules were not scaled down, so flow similarity was not an issue. Both models were of cylindrical shape and made out of paper and Styrofoam. Matching the capsule masses was not an issue since the only job of the OC was to push the air up and around the IC and the IC experiences aerodynamic forces that are independent of its mass. At the beginning of the experiment the scale was set to zero. To create the flow field around the IC the OC was pulled up by the stepper motor with the velocity profile of \( v_{rel}(t) \). This resulted in a net force pointing upwards, which was measurable as a negative “mass” on the scale. Multiplying this value with \( g \) delivered the force acting on the IC. Since this force was below 0.02 N, a scale was required that could measure masses down to 1×10^{-3} kg. Experiments were conducted using two different configurations for the IC: One configuration was with an IC of cylindrical shape, with holes in the side wall so air could freely pass into the IC and one configuration was with an IC that did not have a side wall and consisted of the circular top and bottom plate which were connected by a framework. The dimensional parameters chosen in this experiment were the ones decided on in the previous simulations, which are also those parameters leading to the \( \mu g \) plot in Fig. 8.

The results from multiple experimental runs of the first IC configuration are displayed in Fig. 12. It can be seen that in all cases \( \mu g \) stayed below 1×10^{-3} g. Furthermore, the plot looks similar to its counterpart in the CFD simulations in Fig. 8.

The results from the experiments with the second IC configuration, where the IC model had no side walls, are
displayed in Fig. 13. The maximum \( \mu g \) was around half of that seen in these experiments as it was for the first configuration. These results suggest that an aerodynamic cover for the IC in the form of a cylindrical sidewall is probably not beneficial to the \( \mu g \) of the dual capsule design, which is why it was decided for the IC only to consist of a base frame, much as it is the case for the QUT drop capsule.  

4. Conclusion

In the introduction it was explained that a quality of microgravity \( \mu g \leq 10^{-5} \) is a requirement that has so far not been achieved at non vacuum drop towers. This was a central requirement for the non-vacuum drop capsule design presented in this paper. With the combination of an analytic solution for the capsule motion and computational fluid dynamics simulations an outer capsule design was developed. Furthermore, the dimensions of the inner capsule and outer capsule were optimized.

Given the research described in this paper this capsule design will likely deliver the required quality of microgravity under the restriction that the masses of the inner and outer capsule are at least as large as assumed, and the drag coefficient of the outer capsule is as small as the simulations in section 3 suggest. An alternative solution was presented in case the drag coefficient is too large, consisting of increasing the outer capsule mass. This results in a range of possible outer capsule masses for which the release mechanism and deceleration device will need to be designed to work with.

Additionally, the preliminary drop tower design was presented and described.

Acknowledgments

The author wants to acknowledge the Cooper Foundation in Waco, Texas, funding the BU drop tower and Dr. René Lauffer, Dr. Truell Hyde and Dr. Georg Herdrich for their great project supervision.

References

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