Feasibility of DLR's STG-ET vacuum chamber for simulation of the VLEO environment

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Within recent years, the very low earth orbit (VLEO) has seen a massive gain in interest for future long term satellite missions, especially within the field of earth observation and communications. Development of systems for such missions can be challenging, since the residual atmosphere in the desired orbits significantly changes mission requirements. While the existence of a residual atmosphere enables new mission concepts such as air-breathing electric propulsion (ABEP) and aerodynamic maneuvers using satellite surfaces, it also means that satellite systems are exposed to higher grades of erosion due to interaction with the residual molecules, especially atomic oxygen. Therefore, the qualification of such systems becomes increasingly important. This work shall represent the operational capabilities of DLR's "Simulationsanlage für Treibstrahlen Göttingen – Elektrische Triebwerke" (STG-ET, Simulation Facility for Thrusters Göttingen – Electric Propulsion) facility with respect to the simulation of the VLEO environment. The large volume of the facility gives the possibility to test complete (sub-) systems such as thrusters or satellite components under high vacuum conditions, due to the capabilities of the vacuum pumping system, consisting of multipleturbo- and cryopumps. The operational experience and parameters of such a large-scale research facility as well as concepts for the simulation of the VLEO environment will be discussed. A possible experiment could be the integration of an ion source within the facility to simulate the atmospheric flow conditions present in the VLEO environment, resembling a rarefied gas wind tunnel, similar to experiments on the interaction of satellite surfaces with hypersonic rarefied gas flows conducted at DLR Göttingen in the 1970s, which will also be presented briefly. Such

an experimental setup would allow to research the interaction of highly rarefied, ionized gas flows with satellite components and structures. The pumping capabilities of the facility allow the testing of electric propulsion, which has been its main purpose so far but also becomes interesting within the context of ABEP. A special focus shall be put on the possibility to conduct long-term test campaigns within the scope of weeks or months within the facility, which has been proven successfully within previous experimental campaigns for the industry. Therefore, the qualification of systems for the VLEO environment seems feasible within the STG-ET facility. Further activities and facilities at the DLR Göttingen related to electric propulsion and rarefied gas flows will be discussed.

1. Introduction

With the growing interest for missions within the very low-earth-orbit (VLEO), especially for earth observation and communications [1], the advancement of understanding of the interaction of the spacecraft with the residual atmosphere becomes necessary. The applications of interest are e.g. aerodynamic maneuvers for satellites [2], in situ resource utilization for air-breathing electric propulsion (ABEP) [3] as well as aerocapture or aerobraking for re-entry missions [4]. These missions are often planned to operate for years, making the qualification of the equipment necessary. In addition, the mission analysis and design require experimental data to verify numerical results [5]. While (thermal) vacuum chambers to reproduce the space environment in low-earth-orbit (LEO) or for geostationary orbits (GEO) are quite common, facilities which reproduce the conditions in the VLEO, especially the high-velocity flow ($v_\infty \approx 8$ km/s) of the neutral atoms of the residual atmosphere are quite rare[6]–[9]. With the increase of demand for such facilities, it becomes therefore necessary to establish or upgrade more 'wind tunnels' capable of recreating such an environment. The main challenges are here the pumping capabilities for gas flows within the chamber as well as the acceleration of flows to the free-stream velocity observed in LEO. This work shall demonstrate some of the capabilities of the vacuum wind tunnels and chambers at the Institute of Aerodynamics and Flow Technology at the DLR Göttingen and modifications or extensions necessary to study high velocity, low density flows as they occur in the VLEO. While there are multiple facilities available, some of which have up to 50 years of operational experience [Ref VXG], this work will focus mainly on the STG-ET facility, which has been built 10 years ago with a special focus on long-duration test campaigns for the qualification of electric propulsion [Ref STGET]. Since the vacuum systems of this facility is designed to resemble the space environment, the atmospheric conditions in terms of pressure and density of the LEO are well within their operational range. Still, the creation of a low-density, high velocity flow of neutrals is very challenging, therefore different methods of flow creation and their possible implementation will be discussed. The design methods for the VxG facility, which has been built in the 1970s to study low-density hypersonic flows using the molecular beam technique, will be implemented for the STG-ET facility. Finally, the feasibility of the STG-ET facility for the simulation of atmospheric flows will be evaluated and possible upgrades will be described.

2. Conditions in the VLEO

The very-low-earth-orbit (VLEO) is used as a term to describe an orbit in between heights of 200 km to 450 km above the ground [1], which offers advantages for earth-observation missions. Within the VLEO, flow conditions are dominated by the residual atmosphere, mostly consisting of atomic oxygen. The number densities n of the most important species within the residual atmosphere are displayed in Fig. REF as a function of height according to the empirical NRLMSISE-00 model [10]. It can be seen, that between 200 km and 450 km besides molecular oxygen (O2) and nitrogen (N2), atomic oxygen (O) becomes the most dominant species. Additionally, the temperature, pressure, density, mean free path and Mach number are displayed in Fig REF2. To calculate the Mach number, the velocity is assumed to be the orbital velocity neglecting the drag forces of the residual atmosphere, resulting in a free stream velocity of $v_\infty \approx 8\ \mathrm{km/s}$. Additionally, the Knudsen number has been calculated with a reference length of $L = 1\mathrm{m}$. It can be seen, that depending on height, a free molecular flow cannot be assumed and a transitional regime or slip-flow is more likely to occur, especially for larger spacecraft.

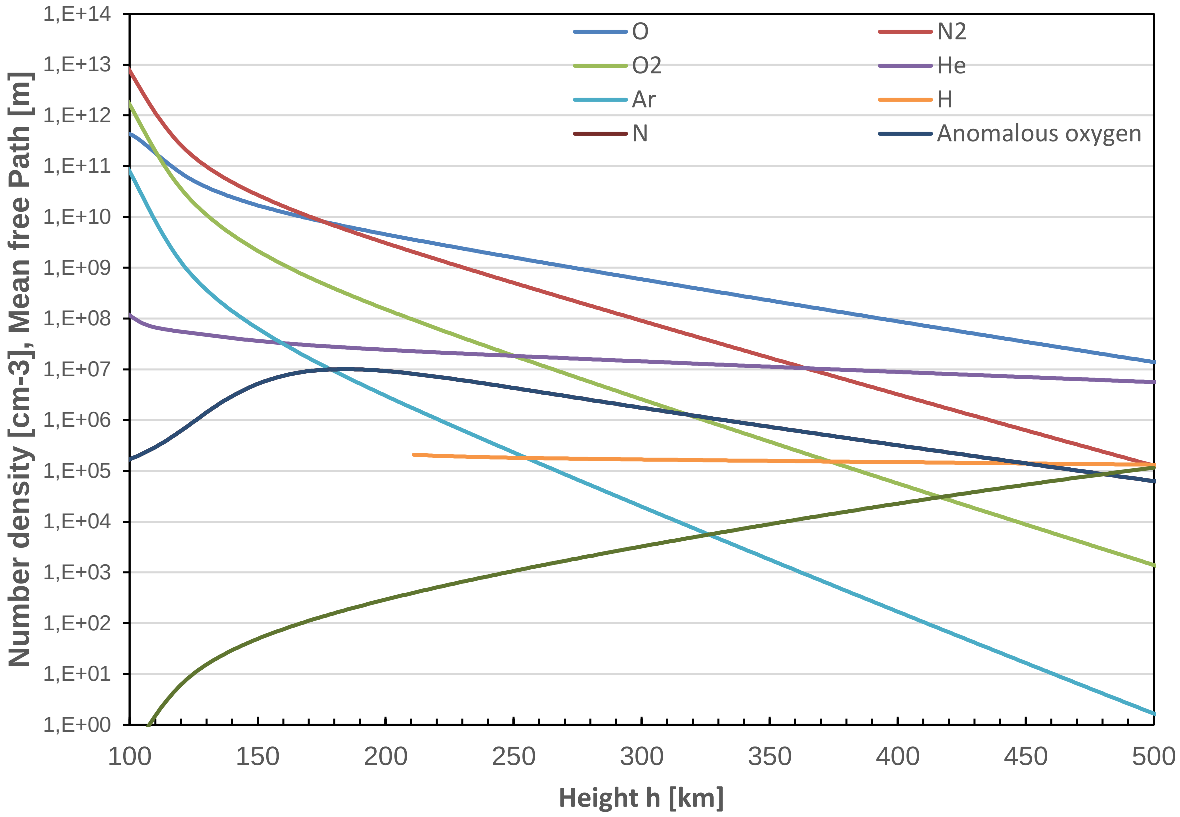


Figure 1: Number Density of molecular oxygen (O2) and nitrogen (N2), atomic oxygen (O) and nitrogen (N) and helium (He), argon (Ar) and hydrogen (H) as well as anomalous oxygen according to the NRLMSISE-00 model as a function of height above ground. Mean free path of air using the total number density as a function of height.

3. Vacuum chambers and wind tunnels at DLR Göttingen

The simulation of rarefied flows has a long history at the DLR in Göttingen, therefore multiple vacuum chambers and wind tunnels are available which can produce the necessary low pressures and densities to recreate environments similar to the atmosphere at high altitudes or space. The different facilities are listed with references in Tab REF. Since these vacuum chambers are used for the testing of propulsion, they are not capable of producing the necessary flow conditions on their own. In the 1970s, the vacuum wind tunnels V1G, V2G [11], [12] and V3G [11], [13] ('Vakuumwindkanal Göttingen') were used to study the aerodynamics of satellites within hypersonic rarefied flows. Since the V1G vacuum wind tunnel has been dismantled, only the V2G and V3G shall be briefly described, while further information can be gained from the descriptions by Koppenwallner [11] and Wuest et al. [12].

Table 1: List of Vacuum Wind Tunnels and Vacuum chambers available at DLR Göttingen

Chamber	**Type**	**Pressure [mbar]**	**Dimensions (LxD)**	**Mean Free Path of Air molecules [m]**
V2G [11]	Vacuum Wind Tunnel	1E-3	6x0.4m	0.0094
V3G [11]	Vacuum Wind Tunnel	1.5E-8	2.5x1.25m	0.008
STG-MT	Propulsion Test	3E-6	2x1m	3.14
STG-ET [11],[12]	Propulsion Test	4E-7	12.2x5m	23.5
STG-CT [16]	Propulsion Test	1E-10	6.25x1.6m	1200

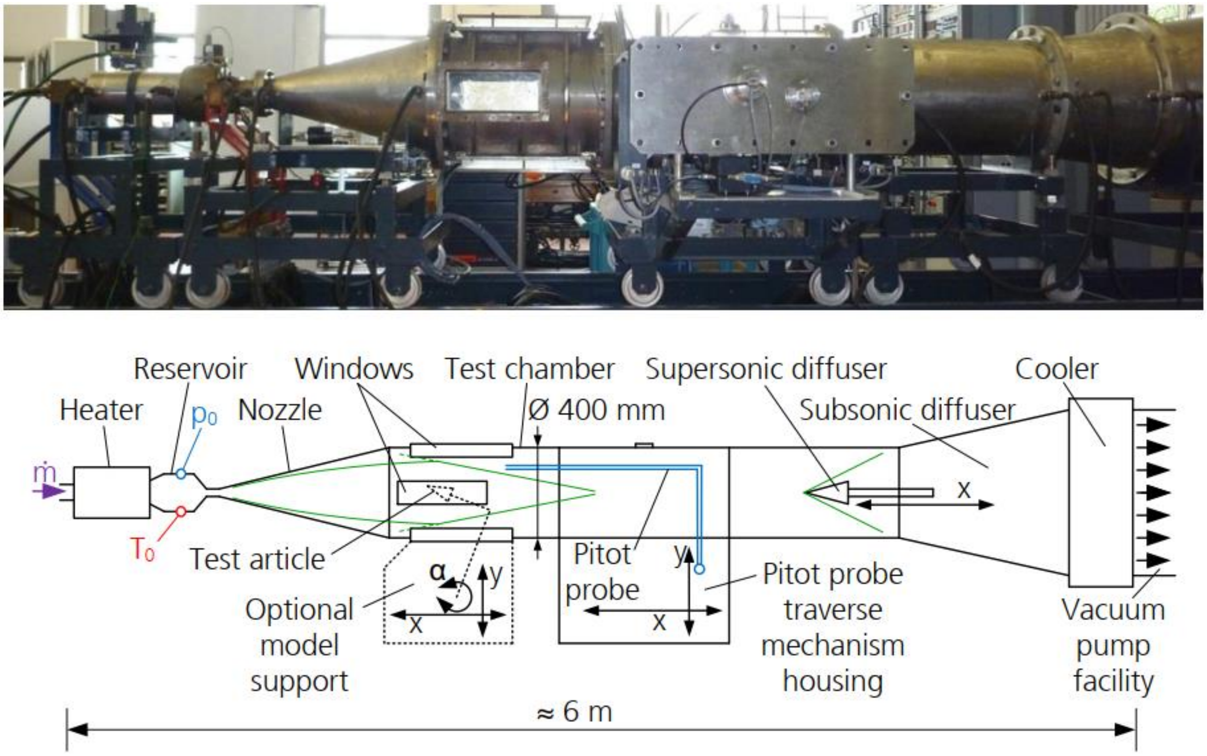
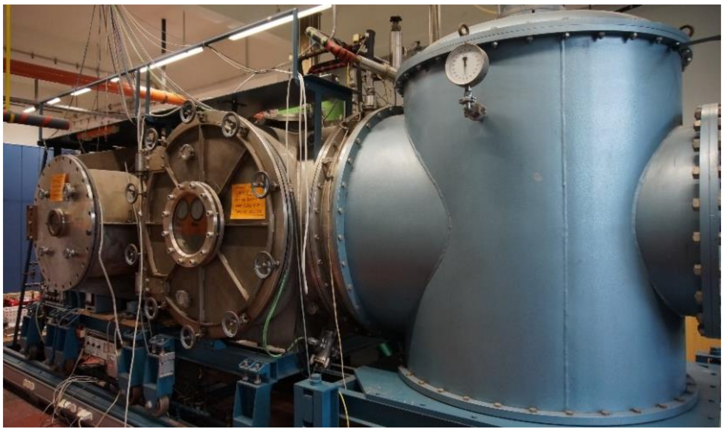


Figure 2: Picture and diagram of the V2G Vacuum Wind Tunnel [17]

Within a hypersonic vacuum wind tunnel such as the V2G and V3G available at the DLR, high Mach number flows are created by the expansion of a gas due to a large pressure difference between the vacuum background pressure and the reservoir pressure. Due to the decrease in temperature of an expanding gas, for a very high flow velocity, the gas also needs to be heated within the reservoir to avoid condensation within the nozzle, which can be done either by an graphite heater as used in the V2G wind tunnel (displayed in Figure 2) or the use of an inductive plasma heater initially used at the V3G [18]. Since the heating of the gas is sometimes not desired and this technique also does not avoid the formation of a large boundary layer, another technique to create the desired flows can be used.



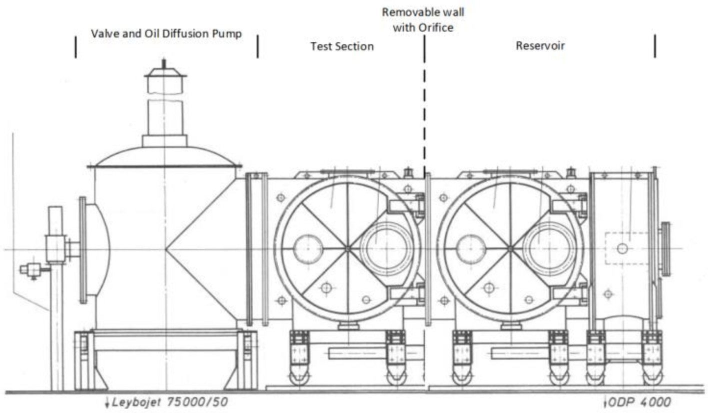


Figure 3: Picture and diagram of the V3G Vacuum Wind Tunnel

At the V3G facility, as shown in Figure 3, the vacuum chamber of the wind tunnel is separated in 2 segments, with a test section and a reservoir separated by a skimmer and collimator. The resulting Knudsen effusion through an orifice is then sufficient to create a molecular free stream with the desired velocities and densities and a very homogenous velocity distribution within the molecular jet with a Mach number $Ma = 7$ at a mean free path of around $\lambda = 8$ mm. The pumping system of the facility consists of multiple roughing pumps, while the final vacuum pressure can be reached using two oil diffusion pumps, on installed in the test section and on in the reservoir section. In addition, the chamber walls can be cooled by using liquid nitrogen, giving additional cryogenic pumping capacity.

Figure 4: The STG-CT facility with door open and view onto helium cryo pump

For the testing of chemical propulsion, the STG-CT [16] ("Simulationsanlage für Treibstrahlen Göttingen – Chemische Triebwerke") facility is used, which is designed for extremely low pressures. This is established using a liquid helium-driven cryopump with an area of about 30m^3 which encloses the test section, maintaining a wall temperature of 4.2 K. This inner cryopump, as seen in Figure 4, is completely enclosed by a liquid nitrogen cooled surface, enclosed by the vacuum chamber, which is evacuated using a set of Leybold roots and rotary vane roughing pumps and a turbomolecular pump. With this setup, pressures of up to 10^{-10} mbar can be reached, even with hydrogen still standby pressures as low as 10^{-5} mbar can be reached, making this facility ideal for the research of plume interaction in space.

Figure 5: Picture and diagram of the STG-MT vacuum chamber

The smaller STG-MT chamber, shown in *Figure 5*, was used for the testing of chemical cold gas thrusters and is now used for testing of diagnostics for electric propulsion as well as to study sputtering of materials by electric thrusters [19]. The facility consists of a combined Leybold rotary vane and Roots pump and a Pfeiffer rurbomolecular pump, making it only viable for higher pressures and low gas flows.

4. The STG-ET Facility

Within this section the capabilities of the STG-ET facility, which has been built specifically for the simulation of a space environment, will be described [14], [15]. The facility, shown in Figure 5 and schematically in Figure 6 respectively consists of a vacuum tank with an inner diameter of 5 m and a length of 12.2 m. To create a rough vacuum, a set of two connected Pfeiffer vacuum pumps is used, which can sustain a base pressure of 10^{-2} mbar. Fine vacuum is created using 4 Edwards turbomolecular pumps connected to a second, smaller set of Pfeiffer roughing pumps, reaching a stand-by pressure of 10^{-6} mbar. The pressure can be lowered further by the use of 18 Oerlikon Leybold cryopumps reaching a stand-by pressure of $4 \cdot 10^{-7}$ mbar. With a gas flow into the facility, the nominal pressure is higher, as shown in Figure 8 which displays the vacuum base pressure as a function of cold gas flow rate for argon, krypton and xenon at room temperature [20]. The pumping speeds are $S(Xe) = 276000\frac{l}{s}$ for xenon, $S(Kr) = 360000\frac{l}{s}$ for krypton and $S(Ar) = 452000\ l/s$ for argon. Multiple diagnostics are available within the facility. These are different robotic arms to support the installation of plasma diagnostics for ion beams, a C-shaped set of Faraday cups to measure the beam current from electric propulsion as well as thrust stands for propulsion. The gas composition can be analyzed using a mass spectrometer. A large number of vacuum feedthroughs allows the simple installation of additional diagnostics to support experiments and the use of optical measurement methods through multiple windows. To shield the chamber walls from sputtering due to energetic ions from propulsion, a water-cooled graphite target is installed at the rear end of the chamber and the chamber walls are protected using graphite plates. As displayed in Figure 6 the whole lid of the chamber can be removed allowing easy access and installation of thrusters. The vacuum chamber can operate continuously at low pressures for extended periods of time up to several weeks or months, giving a unique opportunity for long-duration testing of electric thrusters.

Figure 6: Picture of the opened STG-ET vacuum chamber

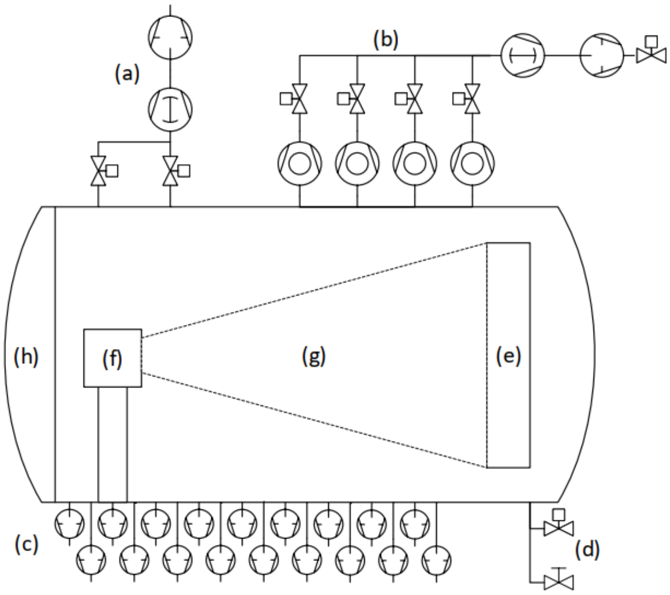


Figure 7: Schematic of the STG-ET facility's vacuum system with (a) Roughing pumps (b) Turbomolecular pumps (c) Cryopumps (d) Venting valve (e) Beam Target (f) Plasma Source / Thruster on Diagnostics Tower (g) Plasma Beam (h) Chamber cove

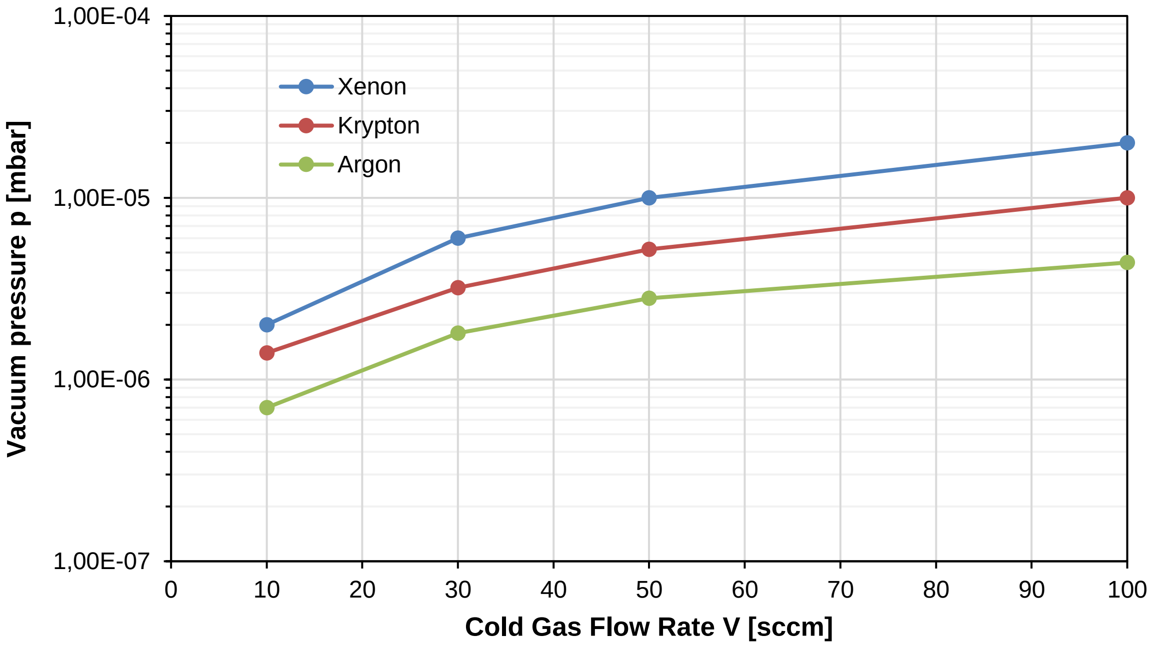


Figure 8: Vacuum pressure of the STG-ET facility as a function of cold gas flow rate for different noble gases [20]

5. Feasibility of the STG-ET facility to simulate VLEO conditions

The generation of flow conditions similar to the atmosphere at high altitudes is one of the most challenging areas of research. While classic Hypersonic Vacuum Wind Tunnels can be used, they are often limited in experimental time, maximum velocity or densities, since they are optimized for specific points within the trajectory of a spacecraft. A similar requirement goes for the simulation of the VLEO, which requires high velocity ($v_\infty \approx 8\frac{km}{s}; Ma_\infty \approx 13$) at very low pressures ($p = 9 \cdot 10^{-7} - 4 \cdot 10^{-9}$ mbar). While the low pressures are possible within some facilities, such as the V3G, STG-CT, STG-ET, the creation of fast atomic oxygen (FAO) flow is challenging. multiple techniques are possible, which mostly require the creation of a plasma, electrostatic acceleration of ions and neutralization of these [9] similar to the neutral beam injection into nuclear fusion devices. While the necessary beam energies required for the atmospheric flow conditions are lower and therefore require much less power, the necessary setup is still very complex and requires multiple vacuum chambers, high voltage acceleration grids and pumps. Another possibility would be the use of an atomic oxygen beam source as described in [9] working by electron stimulated desorption through an Ag membrane, which could be relatively easily installed within the existing facilities. While this setup requires an electron gun and a heater for the membrane, the dimensions, complexity and required energies are significantly lower compared to neutral beam creation. Finally, the molecular beam technique creating a high velocity flow using Knudsen effusion through an orifice could be implemented within the STG-ET facility. To estimate the feasibility of this option, the design considerations of the V3G wind tunnel [13] are applied to the STG-ET facility. For a continuum flow, the mass flow $\dot{m}$ through the exit of a nozzle with exit area A_E is given by

$$\dot{m} = \rho_{\mathrm{E}} u_{\mathrm{E}} A_{\mathrm{E}} = \rho_{\mathrm{E}} u_{\mathrm{E}} \frac{\pi}{4} {D_{\mathrm{E}}}^2$$

in which ρ_E is the density at the nozzle exit. For the exit velocity u_E and Mach number Ma_E, the relation $u_\mathrm{E} = Ma_\mathrm{E}\sqrt{\kappa R T_\mathrm{E}}$, in which $T_\mathrm{E} = T_0\,(1 + \frac{\kappa-1}{2} {Ma_\mathrm{E}}^2)^{-1}$ is the temperature at the nozzle exit in relation to the reservoir temperature T_0, can be used to find a relation between vacuum pump volume flow, exit Mach number and nozzle diameter

$$\dot{V} = \frac{\pi}{4}\sqrt{\kappa R}\,\frac{T_\mathrm{p}}{\sqrt{T_0}} Ma_\mathrm{E}\sqrt{1 + \frac{\kappa - 1}{2} {Ma_E}^2}\,\frac{p_\mathrm{E}}{p_\mathrm{p}} {D_\mathrm{E}}^2$$

using the relation for the mass flow of a pump $\dot{m} = \frac{p_p \dot{V}}{R T_\mathrm{p}}$ in which p_p and T_p are the pressure and temperature at the pump. While in reality, the pressure and temperature distribution within the STG-ET is more complex, especially considering cryopumps, for this simplified analysis we assume that the vacuum pressure is equal to the pressure at the pumps $p_\mathrm{E} = p_\mathrm{p}$. Initially, we will also assume that the temperature at the pump and the reservoir temperature are equal, leading to $T_\mathrm{p} = T_0$.

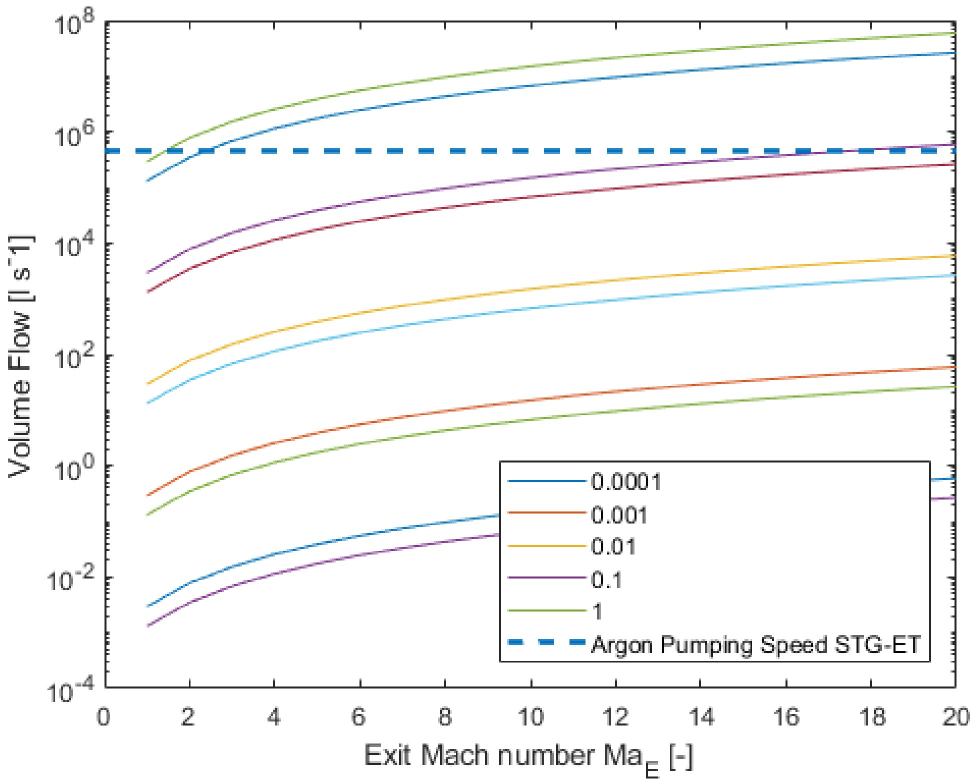


Figure 9: Required pumping volume flow as a function of nozzle exit Mach Number for reservoir temperature of 300K and 1500K for different nozzle exit diameters

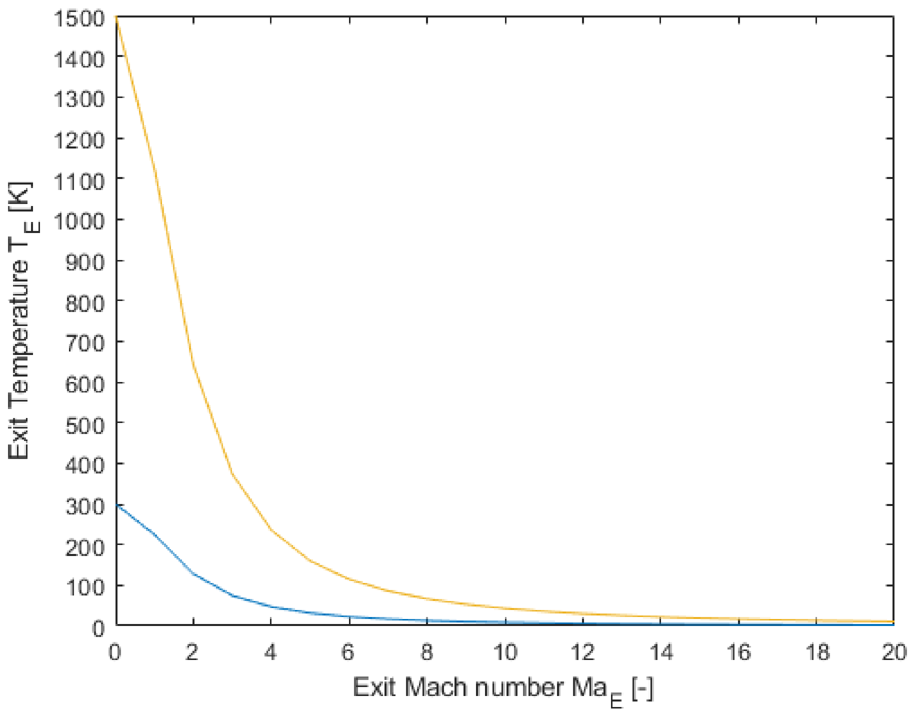


Figure 10: Nozzle exit temperature as a function of nozzle exit Mach Number for reservoir temperature of 300K and 1500K

As it can be seen in Figure 9, in which the necessary pumping volume flow are shown as a function of exit Mach number, for Argon (for which the pumping speed is known) the possible exit Mach numbers can be very high. Unfortunately, as displayed within Figure 10, due to the decrease of temperature during the expansion and the following onset of condensation of the gas, for a reservoir at room temperature a Mach number above 2 is not viable. Even for a heated reservoir similar to the V2G facility or using an inductive plasma heater, the gas will condensate for exit Mach numbers above 6. Additionally, the boundary layer within the nozzle will grow significantly, influencing the center flow. The expansion within an ideal nozzle is not viable for the creation of high velocity flows within the STG-ET facility. Therefore, it is necessary to use a freely expanding jet to generate such a high speed flow. In a free jet, the Mach number along the center line is a function of axial distance x from an orifice with a diameter d [21], [22] given by

$$Ma(x) \; = A \cdot \left(\frac{x - x_0}{d}\right)^{\kappa-1} \cdot (1 - \frac{1}{2}\frac{\kappa + 1}{\kappa - 1})$$

for which the constants are given in Table 2, calculated using the method of characteristics. The distribution of the density along different stream lines is given by

$$\frac{\rho\ (\Theta', x)}{\rho_0} = B\ cos^2\left(\frac{\pi\Theta'}{2\phi}\right)\left(\frac{R}{d/2}\right)^{-2}$$

Table 2: Constants of the free jet for different adiabatic coefficients

κ	$\frac{x_0}{d}$	A	ϕ	B
1.67	0.075	3.26	1.365	0.643
1.4	0.4	3.65	1.665	0.357
1.2857	0.85	3.96	1.888	0.246

For the limiting case of $\frac{\lambda}{d} \gg 1$, when the pressure and density in the reservoir is lowered, the transition to the Knudsen effusion as displayed in Figure 11 begins. Within the reservoir, a Maxwell distribution of the velocities is assumed and within the vacuum chamber, absolute vacuum is assumed. The distribution function of the particle velocity components ξ_{r} in polar coordinates can now be written as

$$f_r = \frac{n_0}{(2\pi R T_0)^{3/2}} \cdot \exp(\frac{{\xi_{\mathrm{r}}}^2}{2RT_0})$$

And the moment on the axis of the Knudsen effusion becomes

$$< \phi\ (\xi_{\mathrm{i}}) > = \int_{\varphi=0}^{2\pi} \int_{\vartheta=0}^{\Theta} \int_{\xi_{\mathrm{r}}=0}^{\infty} \phi\ (\xi_{\mathrm{i}})\, f_{\mathrm{r}}\, {\xi_{\mathrm{r}}}^2\, sin\vartheta d\varphi d\vartheta d\ \xi_{\mathrm{r}}$$

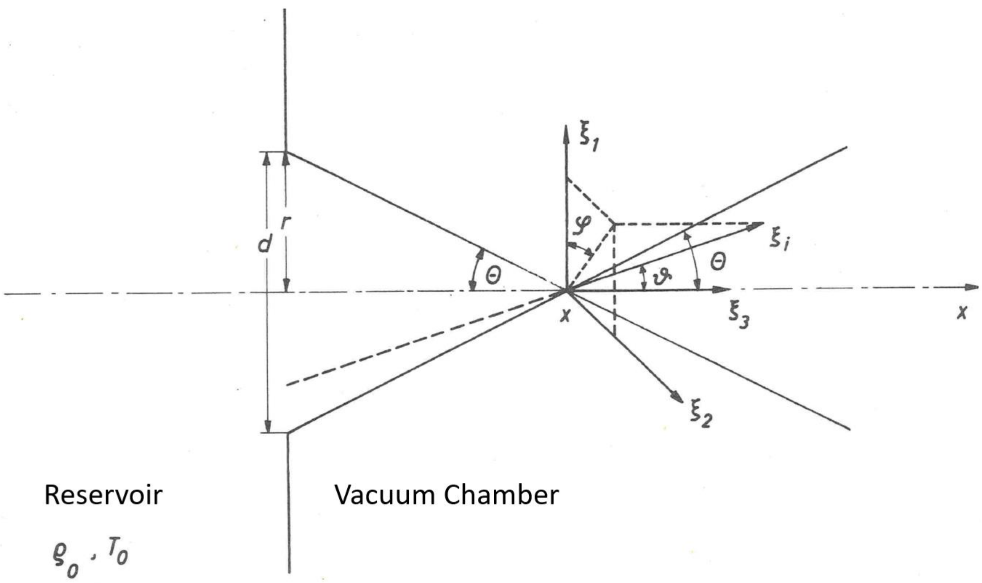


Figure 11: Scheme and variables of the Knudsen effusion through an orifice with diameter d

The values of the flow along the stream can now be written as a function of the angle θ, which can also be written as $\theta = arc\ tg\ \frac{r}{x}$. The variables of the flow now become $n = n_0\, sin^2 \frac{\theta}{2}$ for the number density, $u_i = \frac{2\sqrt{2RT_0}}{\sqrt{\pi}} \left\{0,0, cos^2 \frac{\theta}{2}\right\}$ for the flow velocity and $T = T_0 \left(1 - \frac{8}{3\pi} cos^4 \frac{\theta}{2}\right)$ for the temperature. We can now gain the value for the ratio of molecular speed

$$S = \frac{U}{\sqrt{2RT}} = \frac{2}{\sqrt{\pi}} \frac{cos^2 \frac{\theta}{2}}{\sqrt{\left(1 - \frac{8}{3\pi} cos^4 \frac{\theta}{2}\right)}} = Ma\sqrt{\frac{\kappa}{2}}$$

.

Therefore, in Figure 12 we can now display the axial distribution of the Mach number a freely expanding jet for the flow within continuum and also for the limit of free molecular flow.

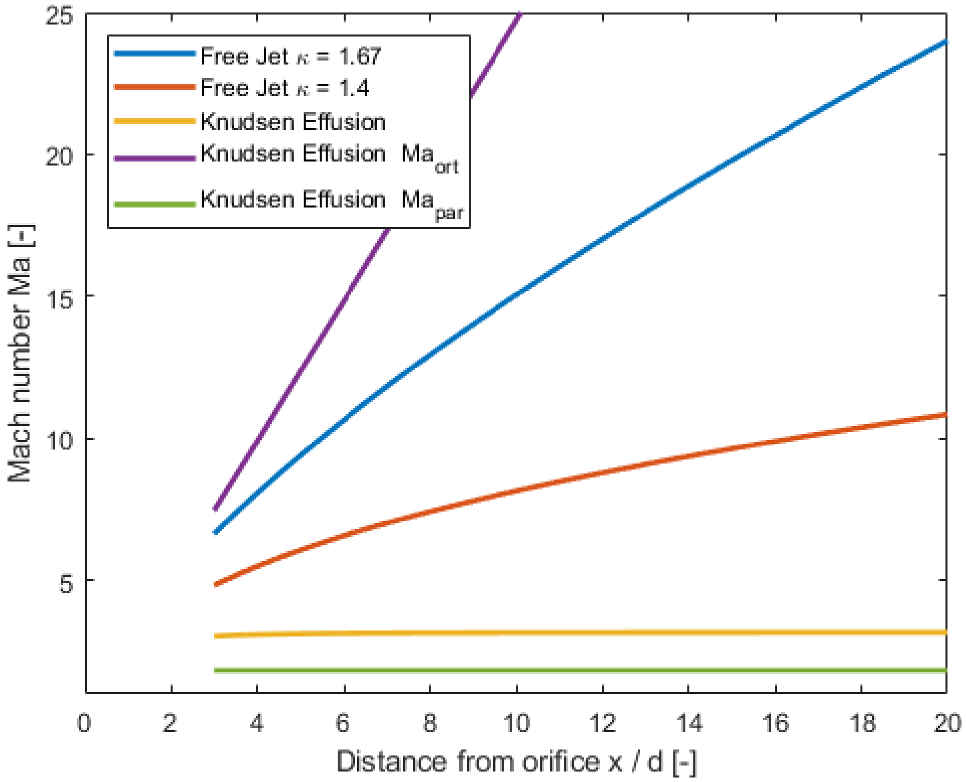


Figure 12: Axial Mach number of a free jet within a continuum flow and parallel and orthogonal Mach number for the limit of Knudsen effusion as a function of dimensionless distance x/d from the orifice

As we can see, within a free jet, very high Mach numbers of up to 20 for Argon or 13 for nitrogen can be reached. The position of the compression shock at the end of the free jet can be found from $\frac{x_\mathrm{M}}{d} = 0.67\left(\frac{p_0}{p_\mathrm{p}}\right)^{1/2}$ with the chamber pressure p_p. This ratio is independent of adiabatic coefficient, condensation or nozzle geometry. Since in the STG-ET due to its high pumping capacity and very low pressures, a high ratio of $\frac{p_0}{p_\mathrm{p}} > 1000$ can be assumed even if the reservoir is just at atmospheric pressure, $\frac{x_\mathrm{M}}{d} \approx 21$, therefore a very high Mach number can be reached just by the expansion of a free jet into the vacuum of the chamber. This is again limited by partial condensation of the gas and the limit in which for the density of the free jet becomes so low which is comparable to the background pressure of the vacuum chamber.

6. Conclusions

A brief overview of the different vacuum chambers and wind tunnels at DLR Göttingen has been given to demonstrate their capabilities to simulate the VLEO. It has been found, that in terms of pressures and pumping capacity, the V3G vacuum wind tunnel and the STG-ET vacuum chamber are the most viable options to create such a facility. These facilities also have rather large dimensions, making it possible to also test larger types of equipment and neglect the influence of reflections from the chamber walls. The analysis of the viability has been done by employing the calculation methods for a free jet used for the design of the V3G wind tunnel on the parameters STG-ET facility. It has been found that very high Mach numbers can be reached by expanding a (molecular) free jet through an orifice until the limit of Knudsen expansion. Other techniques to achieve high velocity flow of neutrals, such as an atomic oxygen source or neutral beam injection using the acceleration of a plasma are also viable but require further study of these technologies. Additionally, the pumping capacity of the STG-ET facility has been tested with noble gases only, and a measurement of the pumping speed for air, nitrogen and oxygen is necessary to further understand the feasibility of the facility for the simulation of the VLEO or other orbital environments. Based on these analyses, a more detailed design of a VLEO wind tunnel can be obtained in the future.

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