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Numerical Investigation of High Temperature CO2-N2 Flows in a Plasma Wind Tunnel Facility

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Abstract

Recent interest in missions to Mars brings about the necessity for ground based testing of the flows experienced during entry into the Martian atmosphere. Located at the Bundeswehr University in Munich is an arc-heated plasma wind tunnel that can provide steady-state, high-enthalpy CO_2 flows at realistic entry conditions into Martian atmosphere. Previous experimental work using two-photon laser-induced fluorescence (LIF) excitation spectra of carbon monoxide provides temperature profiles of the nozzle flow from the plasma wind tunnel, enabling the validation of numerical modelling approaches to this nozzle flow. The objective of this study is to improve the numerical prediction of the Bundeswehr university's plasma wind tunnel by considering the effect of adding N_2 to the flow as a diluent. Four N_2 dilution ratios were considered at stagnation enthalpies of 16 MJ/kg and 19 MJ/kg (including the enthalpy of formation of CO_2). At higher stagnation enthalpy the N_2 mass fraction was found to increase nozzle flow temperature by up to 13%, while the effect of N_2 only had a slight effect at the highest dilution ratio for the low-enthalpy case. The CO mass fraction was found to be affected less in the high-enthalpy case than in the low-enthalpy case, expected to be due to dissociation of CO in the nozzle. For the mixture representing Martian atmosphere the hot core flow was found to be slightly smaller in the high-enthalpy case, however the general shape of the jet was very similar. The results of the present study provide a good basis for numerical validation with future experimental results.

Keywords: *plasma wind tunnel, carbon dioxide, Mars atmosphere, nitrogen modelling*

1. Introduction

In order to cost effectively test the technologies required for high-speed atmospheric flight on planets such as Mars, the support of ground based test facilities capable of producing flows which account for high-enthalpy real gas effects is required. Future proposed interplanetary missions will rely on investigation of the Martian atmosphere, and in particular the space vehicle entry into that atmosphere. The entry process results in high temperatures on the vehicle surface, and therefore the environment to which it is exposed requires careful characterisation. The Institute for Thermodynamics at the Bundeswehr University Munich (UniBw) operates an arc-heated Plasma Wind Tunnel (PWT) facility. The high enthalpies and long test duration that can be achieved using the PWT makes it ideal for use in the present study. The UniBw-PWT facility is capable of adding total enthalpies of up to 20 MJ/kg to the flow and stagnation temperatures in the order of 6000 K in the arc chamber.

The facility has been adapted to operate using CO_2 as the test gas. The addition of a sealed test chamber, connected to a high efficiency vacuum pump allows the facility to produce specific enthalpies

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and pressures simulating the conditions prevailing during the entry into Mars atmosphere. In the case of CO_2 as test gas, the operational envelope of the facility is shown in Fig. 1.

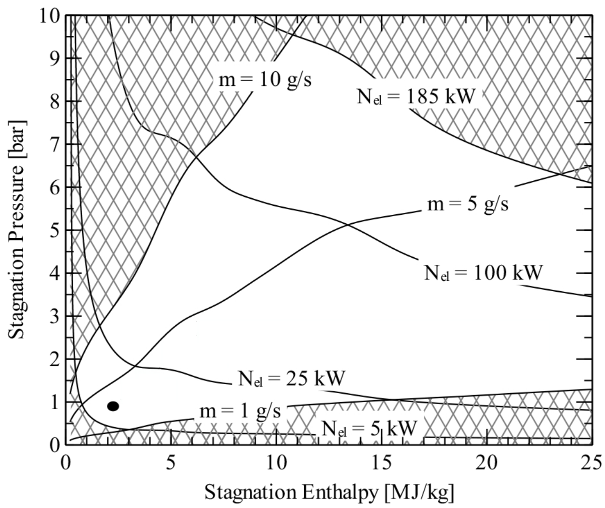

Fig 1. Operational envelope of the PWT using CO_2 as test gas [7].

In spite of N_2 being present in small percentages, it is considered to be an important species in Mars atmosphere. In addition, the exact percentage varies within the atmosphere of Mars. Because it is rather difficult to make fine adjustments to the N_2 mass fraction in the PWT, Computational Fluid Dynamics (CFD) provides an excellent opportunity to conduct a sensitivity study on the effect of N_2 on a supersonic CO_2 flow. The complementary capabilities of numerical tools such as CFD are critical in order to further predict and explore these flows, however the impact of modelling simplifications on prediction accuracy need to be understood if the numerical results are to be of use.

At low enthalpies, the effect of N_2 addition has been considered to be negligible, and hence has been neglected in numerical simulations that have been conducted so far [4], however as the enthalpy increases the impact is expected to increase. The present study aims to numerically investigate the effects of introducing N_2 into the UniBw-PWT flow, across previously unexplored stagnation enthalpies of 16 MJ/kg and 19 MJ/kg. The starting point of the study is a typical Martian atmosphere (97% CO_2 and 3% N_2) [3], in which the N_2 will be slightly altered to determine the effect of N_2 dilution ratio on the temperature and CO profiles of the UniBw-PWT nozzle flow.

2. Numerical method

The commercial solver CFD++ [2] is used for all calculations. CFD++ solves the steady, compressible Reynolds-Averaged Navier-Stokes equations and includes finite rate chemistry with multiple species. Interface fluxes are defined using Riemann solvers based on local wave-model solutions. All calculations in the present study utilise a steady state implicit (backward Euler) numerical scheme and a second order accurate spatial discretisation utilising Total Variation Diminishing polynomial interpolation [2].

Turbulence was modelled using Menter's two-equation Shear Stress Transport (SST) k-ω model. The SST model utilises the k-ω formulation close to the wall, blending to the k-ε model towards the freestream. This model is less sensitive to specification of freestream turbulence level compared to the k-ω model and performs comparatively well in adverse pressure gradients and separated flows. Modelling of chemical kinetics is done using the 103 reactions, 11 species (CO_2, CO, C_2, O_2, N_2, NO, CN, CNO, C, N and O) reaction mechanism detailed in the "Report and Library on Gas Phase Chemistry" by Fertig [3], to account for the presence of N_2. In the present study, four different nitrogen dilution ratios (0%, 3%, 5% and 10%) are examined at two stagnation enthalpies (16 MJ/kg and 19 MJ/kg, including the enthalpy of formation of CO_2). The enthalpies are selected to examine the effect of stagnation temperature on

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the nozzle flow and to explore a previously uncharted operating condition of the UniBw-PWT. The gas compositions at these conditions were obtained using the CEA program [5, 6] at a stagnation pressure of 90 kPa and are presented in Table 1. The enthalpy of CO_2 at room temperature was considered the zero-enthalpy point in these calculations, i.e. the 16 MJ/kg condition represents heat addition of 16 MJ/kg to CO_2 at room temperature. Table 1 contains the stagnation temperature and mass fractions of major species for each of the test conditions investigated. As can be seen, most of the CO_2 has dissociated into CO at the higher enthalpy cases and between 25%-30% of the N_2 has dissociated.

Both the nozzle and a small section of the test chamber were modelled. Grids were constructed using the commercial meshing software Pointwise with a two-dimensional, fully structured 2D-axisymmetric approach and are shown in Fig. 2.

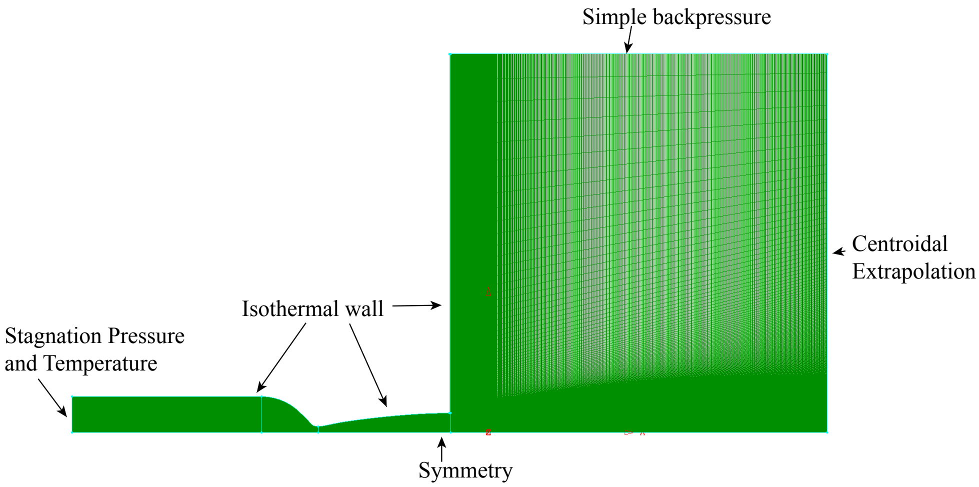

Fig 2. Mesh of the plasma windtunnel showing boundary conditions.

Cell refinement was achieved manually in critical regions such as the nozzle throat to achieve a y^+ value of approximately 1.0. The centreline was given a symmetry boundary condition, while the nozzle wall was given an isothermal wall type boundary condition with a fixed temperature of 300 K (due to active water cooling in the UniBw-PWT) that is solved to the wall. At the inflow, stagnation conditions were prescribed, where the stagnation pressure was held constant at 90 kPa and the stagnation temperature and gas composition were applied for each case according to the compositions in Table 1. The vertical outflow boundary that contains the nozzle jet was prescribed a no conditions prescribed centroidal extrapolation boundary condition while a back pressure of 4500 Pa was applied to the top outflow boundary. The exhaust chamber was initialised with air at 300 K, so the CO_2 mixture is exhausting into air.

To assess grid convergence the method proposed by Roache [8] was used, which is based on Richardson extrapolation. The approach uses three grid refinements to obtain a quantitative estimate of the discretisation error in a grid, by estimating its value in the limit of grid spacing tending to zero. This method was implemented according to the procedure outlined by Celik et al. [1]. Massflow was selected as the refinement variable for the procedure. The grid convergence was calculated for the reacting case, using the case with a stagnation enthalpy of 16 MJ/kg and gas composition with 97% mass fraction CO_2, and 3% mass fraction N_2.

To obtain the three grid refinements, the characteristic size h of the initial mesh was computed as follows

$$h = \left[\frac{1}{N} \sum_{i=1}^{N} (\Delta A_i) \right]^{\frac{1}{2}} . \tag{1}$$

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Table 1. Inflow boundary conditions. Gas composition is presented in species mass fraction.

	T [K]	CO_2	CO	O	O_2	N_2	NO
16 MJ/kg, 0% N_2	4196	0.0247	0.621	0.302	0.0522	0.0	0.0
16 MJ/kg, 3% N_2	4220	0.0216	0.604	0.293	0.0454	0.0244	0.0111
16 MJ/kg, 5% N_2	4219	0.0208	0.591	0.287	0.0436	0.0428	0.0144
16 MJ/kg, 10% N_2	4241	0.0175	0.562	0.273	0.0370	0.090	0.0196
19 MJ/kg, 0% N_2	5577	7.11×10^{-4}	0.634	0.363	0.0184	0.0	0.0
19 MJ/kg, 3% N_2	5493	7.90×10^{-4}	0.615	0.349	2.03×10^{-3}	0.002	3.83×10^{-3}
19 MJ/kg, 5% N_2	5540	6.88×10^{-4}	0.602	0.342	1.77×10^{-3}	0.0359	4.85×10^{-3}
19 MJ/kg, 10% N_2	5649	4.98×10^{-4}	0.569	0.324	1.29×10^{-3}	0.0758	6.24×10^{-3}

The cell density in both dimensions was then increased to obtain the medium and fine mesh. The representative mesh size for the new grid was computed, until a grid refinement factor $r = h_{coarse}/h_{fine}$ of at least 1.3 was achieved. The number of cells for each mesh is shown in Table 2, along with their representative mesh size.

Table 2. Grid refinement statistics.

Grid	n_{cells}	h_n(mm)	Refine factor
Fine (h_1)	777,174	0.2345	$r_{21} = 1.402$
Medium (h_2)	395,526	0.3287	$r_{32} = 1.427$
Coarse (h_3)	194,336	0.4690	-

To obtain the discretisation error estimate for the medium grid, the mass flow through the nozzle inflow boundary was used. For the case outlined here, evaluation of the results yields an approximate relative error of e_a^{21} =0.003% and an extrapolated relative error of e_{ext}^{21} = 0.0023%. This leads to a grid convergence index (GCI) of 0.003% with an (enforced) apparent order of $p = 2$. The two-dimensional mesh used in the study has a high level of grid refinement, even for the coarse mesh, leading to a small GCI. The results of the grid convergence study together with the Richardson extrapolate are shown in Fig. 3. The figure shows that the mass flow is approaching the Richardson extrapolate as the grid grows finer, demonstrating grid independent results.

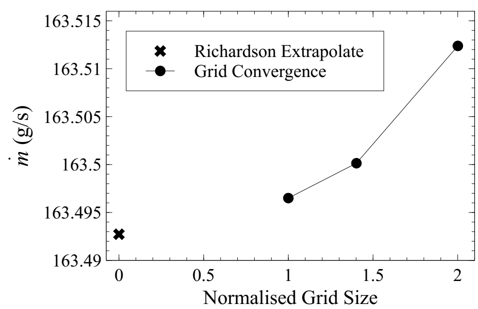

Fig 3. Richardson extrapolation of mass flow $\dot{m}$ at the nozzle outlet.

Figure 4 shows the temperature profile for each grid at the outflow of the nozzle. The plot shows that all grids predict an almost identical temperature profile. For the present study the medium grid has been selected, since it provides a balance between computational accuracy and computational effectiveness. In addition, the higher number of cells in the medium grid compared to the coarse grid could potentially

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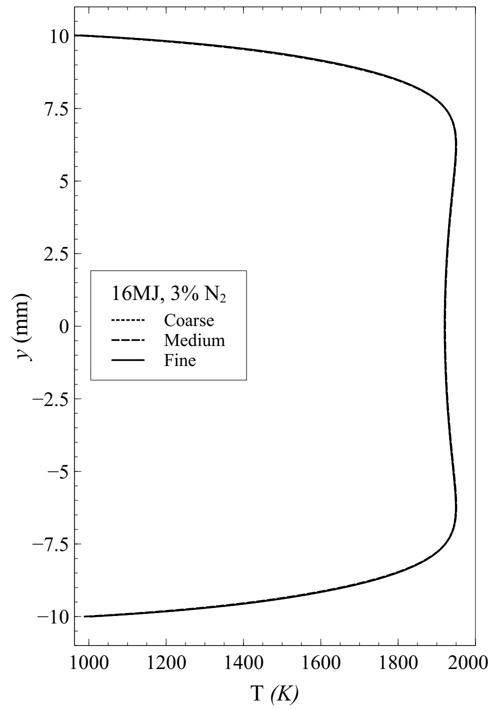

Fig 4. Temperature T profile for each grid refinement at the nozzle outlet.

capture non-linear chemical effects at higher N_2 dilution ratios better.

3. Results

The operation of the UniBw-PWT using CO_2 as test gas and with N_2 dilution at a steady state using a Mach 3.4 nozzle is shown in Fig. 5. Due to a small pressure mismatch in the test chamber, the nozzle flow is slightly overexpanded. During previous experiments in the UniBw-PWT [7] experimental measurements using CO-LIF were taken at a location 2 mm in front of the nozzle exit plane (see Fig. 5) using the technique described by Kirschner et al. [7].

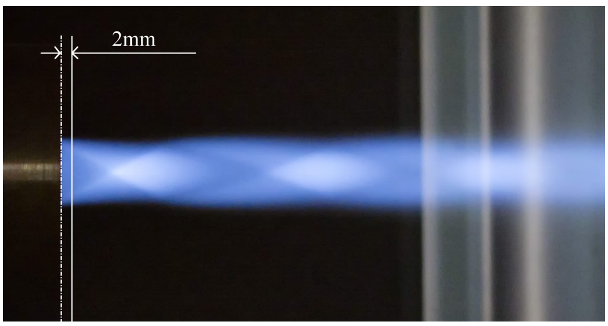

Fig 5. Operation of the PWT with CO_2 as test gas at 11 MJ/kg ($M = 3.4$).

When computing the flow using CFD++ under the conditions specified in Table 1, the nozzle exit flow can be investigated at any location. By taking the centreline plane at the experimental location, direct comparison can be made between the experimental and numerical results. Figure 6 shows the calculated temperature and Mach number contours of the flow using representative Martian atmosphere (proposed by Fertig [3]) and a stagnation enthalpy of 19 MJ/kg. The core of the jet in the CFD result is rather

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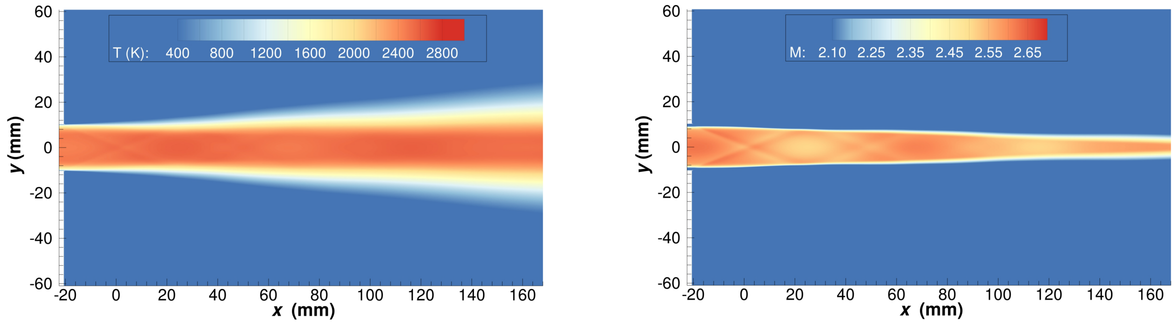

(a) Temperature

(b) Mach number

Fig 6. CFD contours for present study: typical Martian atmosphere composition at 19 MJ/kg ($M = 2.6$).

similar to the jet obtained during experiments, improving on previous results [4, 7], however the Mach number of the flow is 2.6 as opposed to 3.4. This is due to a higher speed of sound in the 19 MJ/kg case due to increased temperatures. The shear layer is quite large in the CFD result, however the jet core is the main focus of the present study. Comparison of Fig. 6b and Fig. 5 indicates that the compression and expansion waves are slightly stronger in the experiment than in the CFD result, however the CFD is sufficiently close to the experimental result.

While the UniBw-PWT is capable of adding a stagnation enthalpy of up to 20MJ/kg, the highest enthalpy addition that has been tested in the past with CO_2 is 11.8 MJ/kg [4, 7]. In the following paragraphs CFD results obtained for the 16 MJ/kg and the 19 MJ/kg operating condition of the tunnel are compared in terms of several variables, to assess how the increased temperature will affect the behaviour of the jet. Temperature and CO mass fraction profiles are compared first for all gas compositions, before the difference in flowfield is examined for the gas composition representing Mars atmosphere. All profiles are obtained 2 mm in front of the nozzle exit to match the experimental measurement location.

3.1. Effect of enthalpy on temperature

Figure 7 shows the temperature profiles for the four gas compositions at both 16 MJ/kg and 19 MJ/kg. Section 3.1 clearly shows that at the lower stagnation enthalpy the effect of nitrogen dilution ratio is minimal; the temperature profile is hardly affected, even in the case with the highest N_2 mass fraction. As enthalpy increases however, the effect of nitrogen is expected to increase, due to increased N_2 decomposition at higher temperatures [3]. Section 3.1 shows the temperature profile for the gas compositions at 19 MJ/kg and it is clear that the N_2 dilution ratio has an effect on the temperature profile.

The figure shows that as N_2 mass fraction increases, the temperature in the core of the jet also increases. This is partially explained by higher stagnation temperatures, as shown in Table 1, however the recombination of atomic N into N_2 is also thought to contribute to this. In general, the temperature is observed to be around 25-40% higher for the 19 MJ/kg operating condition compared to the 16 MJ/kg operating condition.

3.2. Effect of enthalpy on CO mass fraction

Since temperature profiles are measured using CO-LIF during experiments, the CO mass fraction for the different gas composition is also compared, seen in Fig. 8. As N_2 mass fraction increases there is less CO_2, hence it is expected that CO mass fraction will go down as the nitrogen dilution ratio increases. Figure 8 shows that this is indeed the case, however the CO mass fraction varies more with dilution ratio at the lower stagnation enthalpy. One possible reason for this is that in the 19 MJ/kg case more dissociation/recombination occurs than in the lower enthalpy case, dissociating CO into other species.

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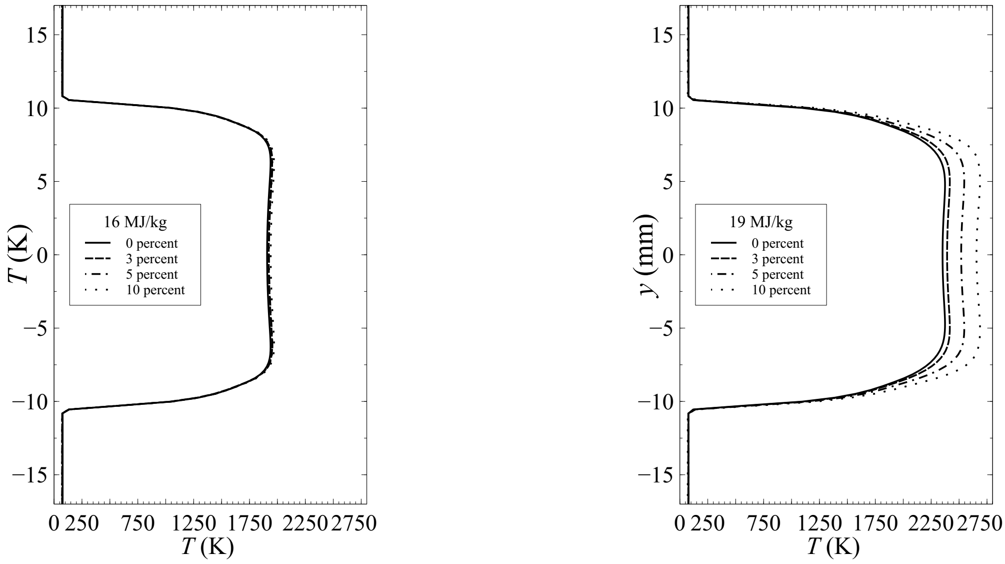
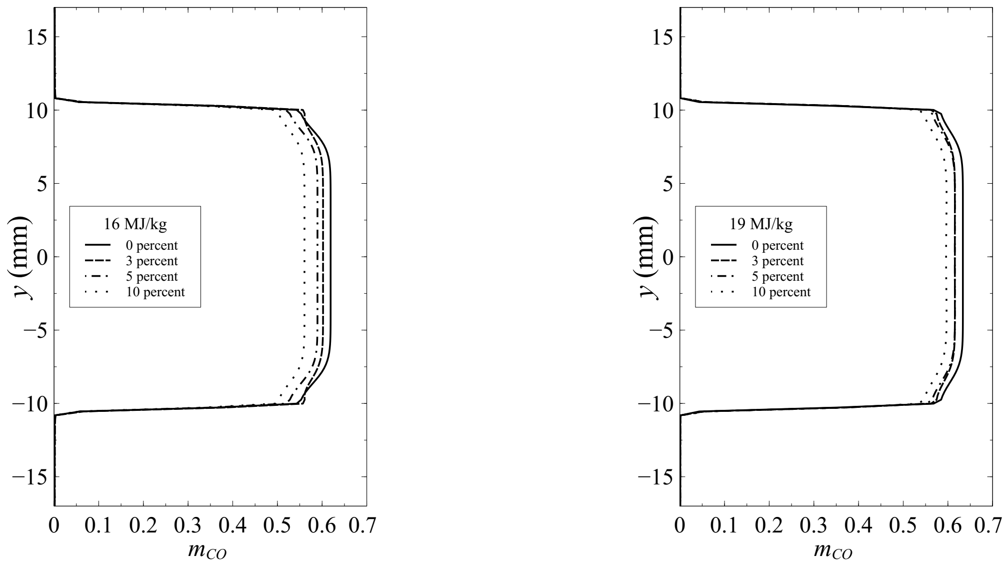


(a) 16 MJ/kg **(b)** 19 MJ/kg

Fig 7. Temperature profiles for four nitrogen dilution ratios at two stagnation enthalpies.



(a) 16 MJ/kg **(b)** 19 MJ/kg

Fig 8. CO profiles for four nitrogen dilution ratios at two stagnation enthalpies.

3.3. Effect of enthalpy on flowfield

An often cited composition of Martian atmosphere is 97% CO_2, 3% N_2. Therefore, the effect of enthalpy on the nozzle flow for this composition is finally examined. The flowfield will be compared first, followed by an examination of the temperature and CO mass fraction profile.

Figure 9 compares the temperature contours between the 16 MJ/kg and the 19 MJ/kg case. While the temperature is higher in the case with the higher stagnation enthalpy, the overall diameter of the jet plume is relatively similar; the increased stagnation enthalpy is therefore not expected to significantly

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alter the shape and size of the nozzle jet.

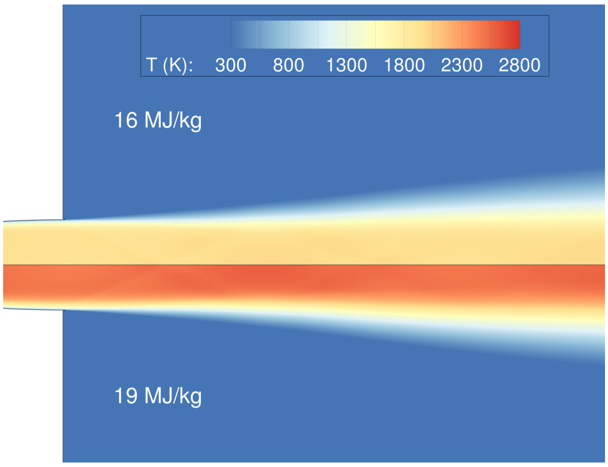
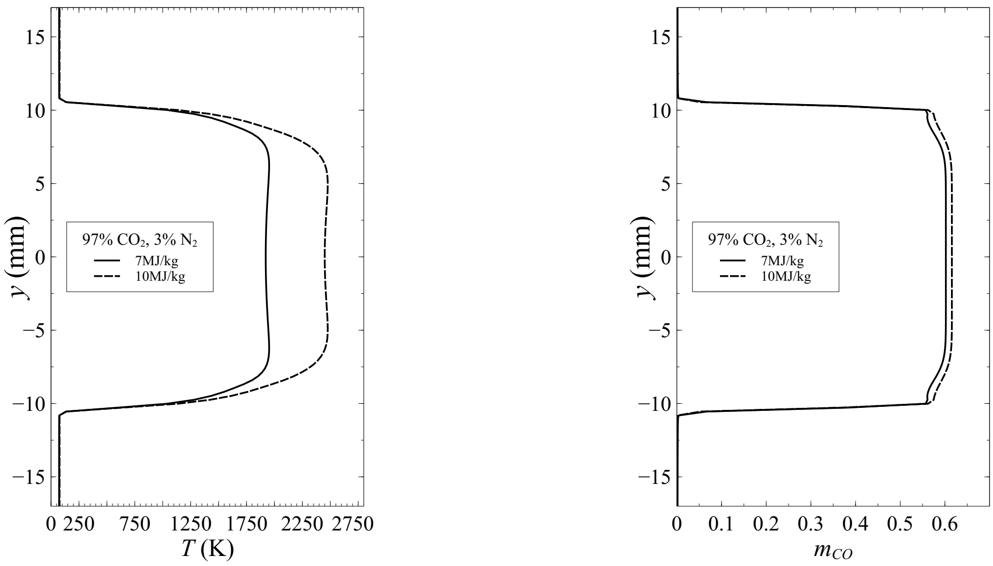


Fig 9. Comparison of temperature contours for 16 MJ/kg and 19 MJ/kg operating condition using typical Martian atmosphere gas composition.

Larger differences can be observed in the temperature profile, shown in Fig. 10. The figure shows that the core of the jet is slightly smaller at the higher stagnation enthalpy, evidenced by the more narrow constant temperature range. The profile also confirms that the diameter of the jet is almost identical in both enthalpy cases.

As can also be seen in Fig. 10, the difference in CO mass fraction is not as large between the two enthalpies. This is again attributed to the fact that CO will decompose into other species at higher gas temperatures.



(a) Temperature **(b)** CO

Fig 10. Comparison of temperature and CO mass fraction profiles at two enthalpies for Martian atmosphere gas composition.

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4. Conclusion

The present study has numerically investigated the effect of stagnation enthalpy and N_2 on the nozzle flow of the arc-heated plasma wind tunnel at the Bundeswehr University. The current study investigated tunnel stagnation enthalpies of 16 MJ/kg and 19 MJ/kg, higher than enthalpies considered in previous studies, using N_2 mass fractions of 0, 3, 5 and 10%.

Numerical modelling showed that N_2 mass fraction had limited influence on the nozzle temperature profile at low enthalpy, however the effect was more profound at the high stagnation enthalpy, as temperature was found to increase by 13% from the lowest to the highest nitrogen mass fraction. CO mass fraction did not change as much as nitrogen mass fraction increased, and the effect of nitrogen mass fraction was found to be larger in the lower enthalpy condition in this case. This is expected to be due to dissociation of CO at the high stagnation enthalpy.

Finally, the effect of stagnation enthalpy on the gas mixture representing Martian atmosphere was examined. The flowfield was found to be very similar for both cases, with the jet core slightly smaller in the high-enthalpy case. The jet core temperature was found to be significantly higher for the higher enthalpy case, with the difference in CO mass fraction again smaller.

Future experimental results at higher stagnation enthalpies will allow an assessment of how accurate the current simulations model the effect of N_2 on the flow. If the numerical predications are still found to be accurate, CFD could be used as a powerful tool to explore stagnation enthalpies that are difficult to achieve experimentally.

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