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Title: Transport properties of high-temperature air species in the presence of a magnetic field
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Executive Summary

Computational Fluid Dynamics (CFD) modelling of high enthalpy flows requires the knowledge of reliable transport coefficients in a wide temperature range. When a vehicle flies hypersonically through the atmosphere the molecules dissociate, ionise, and create a lot of new components. The transport properties are required for each of those components in an appropriately extended temperature range.
In particular, the study of Magneto Hydro Dynamics (MHD) effects in hypersonic flows involves transport processes in partially ionised gases moving in a magnetic field. The presence of the magnetic field breaks the system isotropy so that the transport coefficients acquire a tensorial nature. Recently, calculations were performed for accurate determination of transport coefficients of partially ionised argon in a magnetic field [1]. The calculations employed the Chapman-Enskog (CE) method up to very high orders of approximation to calculate the tensorial transport coefficients of the argon plasma. The present work extends the approach to air plasma [2].

The following objectives have been identified:

- to produce suitable computational schemes of the transport coefficients in tensorial form, including due account of internal molecular structure, of high-temperature air species with a view to implementation in hypersonic-flow solvers;
- to provide numerical tabulations of transport coefficients of these high-temperature air species in the temperature range from 50K to 50000K.

The study considers the general case of ionisation non-equilibrium in a wide temperature and pressure range under the action of an imposed magnetic field. In the present case, the internal structure of the molecular species must be considered in order to account for such transport phenomena as bulk viscosity, relaxation pressure and internal thermal conductivities.

An extensive set of calculations has been carried out in order to provide reference values for all the transport coefficients under a variety of conditions.
Selected results from a few significant cases have been discussed and show the degree to which the anisotropy due to the presence of the magnetic field or the degree of non-equilibrium affect the different transport coefficients.
Finally, numerical tables of transport coefficients in the fifth approximation are given.

Also quoted is the relative error with respect to the fourth approximation.

The following values for the parameters that control the state of the plasma have been considered:

- Pressure. The pressure is considered fixed at 1 atm.
- Temperature. With a fixed value of the magnetic field of 1 T, the temperature is varied in the range 100-50 000 K.
- Magnetic field. The value of B is varied in the range 10^{-3}-100. Calculations are carried out for fixed values of the temperature at T = 13000 K, 35000 K and 50000 K.
- Composition. Several cases have been considered. Each set of calculations considers the plasma composition fixed while the pressure, the temperature and the magnetic field strength are varied. These cases analyse plasma with strong non-equilibrium composition at different ionisation degrees. The following cases have been considered:

  - pure neutral species (N, O, NO, N_2, O_2);
  - non-equilibrium compositions corresponding to fixed-temperature equilibrium compositions.

The air model considered in this work consists of molecular nitrogen (80%) and oxygen (20%). At atmospheric pressure dissociation starts at about 2000 K for O_2 and 3500 K for NO; ionisation starts at about 7000 K, while double ionisation takes place at about 15000 K. The atmosphere is a mixture of 19 components (N, O, N_2, O_2, NO, N^+, N^{2+}, N^{3+}, N^{4+}, O^+, O^{2+}, O^{3+}, O^{4+}, O^-, N_2^+, O_2^+, O_2^-, NO^+, electrons). Equilibrium compositions, considered fixed in non-equilibrium condition simulations, have been obtained by a detailed thermodynamic model of Earth atmosphere components containing accurate treatment of high-lying atomic and ionic energy levels.
It is to be remembered that, due to the anisotropy introduced by the magnetic field, the transport coefficients have tensorial nature. Reported are all the independent tensor components in a frame of reference with one axis parallel to the magnetic field.

The results provide a useful tool to all CFD researchers interested in MHD effects.

[1] D. Bruno, M. Capitelli, C. Catalfamo, A. Laricchiuta, E.V. Kustova, A. Chikhaoui, Transport coefficients of Argon plasma with electromagnetic fields, ESA STR-254, April 2008. ISBN 978-92-9221-902-4.
[2] D. Bruno, M. Capitelli, C. Catalfamo, O. Depascale, D. Giordano, A. Laricchiuta, Transport properties of high-temperature air species in the presence of a magnetic field, ESA STR-260, July 2010. ISBN 978-92-9221-908-6.