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BALLISTIC MISSILE INFRARED SIGNATURE PREDICTION: TESTING CDSD-4000 DATABASE

Rialland Valerie (1), Millot Corentin (1)

(1) ONERA, BP80100, 91123 Palaiseau CEDEX, France, Email: valerie.rialland@onera.fr

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ABSTRACT:

Very few observations of ballistic missiles are available, therefore the design of early warning optronic systems rely mainly on multi-physics simulations. ONERA developed a chain of simulation tools called PRECISE to achieve infrared signature prediction, validated during project SIMBA by an experiment at MASCOTTE test facility. The radiative solver uses a spectroscopic database to estimate the radiation of the most radiative species in infrared, among them CO_2.

Tashkun et al. [1] released in 2011 a new version of CO_2 lines database named CDSD-4000, designed for the temperature range 2500–5000K; it contains 628,324,454 lines for CO_2. Currently, PRECISE radiative transfer code SIR uses HITEMP-2010 database [2], which contains 11,193,609 CO_2 lines. The objective of this paper is to assess the benefit of using CDSD-4000 for infrared signature instead of HITEMP-2010 on several test-cases, including MASCOTTE test-case.

1. INTRODUCTION

Infrared space surveillance sensors are the most effective systems to detect and track proliferating ballistic missiles. These sensors have to be designed and optimized upon realistic infrared signatures of rocket plumes. The lack of observations in operational conditions leads to the use of simulations. ONERA developed a chain of simulation tools called PRECISE to achieve infrared signature prediction. The multi-disciplinary project SIMBA was setup to validate the simulated results from PRECISE by comparison with experimental results. A detailed experimental study was performed at the exhaust of the MASCOTTE test facility with several time-resolved in situ optical diagnostics.

The radiative solver in PRECISE, called SIR for InfraRed Signature in French, uses as an input the spectroscopic database HITEMP [2] released in 2010 in order to estimate the radiation emitted by the hot gases of the missile plumes. However, a new reference database has been issued for CO_2 lines: CDSD-4000 [1].

We will first present the simulation chain PRECISE and project SIMBA, then the CDSD-4000 database. Simulated results with HITEMP-2010 and CDSD-4000 will be compared to calibrated measurements, first in simplified test-cases, then in the case of the MASCOTTE experiment. As a conclusion, the pros and cons of using CDSD-4000 will be discussed. Finally, insights on project SIMBA2 will be given.

2. PROJECT SIMBA

2.1. Simulation chain PRECISE

The infrared signature (IRS) modelling of rocket plumes is a challenging problem involving rocket geometry, propellant composition, combustion modelling, trajectory calculations, fluid mechanics, atmosphere modelling, gas and particles radiative properties, and radiative transfer through the atmosphere. ONERA decided to tackle this complex problem through a common project involving several research teams: SIMBA (French acronym for Ballistic Missile Signature). We developed a chain of simulation tools in order to achieve the infrared signature prediction of rocket plumes. This chain, named PRECISE (Plateforme de Recherche pour l'Evaluation de la CInématique et des Signatures d'Engins), encompasses several in-house codes: first, COPPELIA is a thermodynamic equilibrium code that computes the motor specific impulse, the temperature and the gaseous species composition in the combustion chamber as a function of the propellant composition and the nozzle expansion ratio. The chamber temperature, pressure and gaseous composition, the rocket speed, altitude and geometry are used to initialize ONERA Computational Fluid Dynamics (CFD) code CEDRE for the plume flow field computation. CEDRE [3] is a multiphysics computational tool for numerical simulation in the field of energetics, with particular emphasis on propulsion applications. The aerothermochemical cartography of the plume computed by CEDRE is transposed on a structured mesh for the last step of the modelling chain: the radiative transfer computation. Our infrared signature computation tool, named SIR, takes as input the pressure, temperature, mass fraction of H_2O, CO_2, CO, HCl, alumina particle density and
temperature. It can perform radiative transfer computation in a hot non-scattering medium with either a line-by-line model or a statistical narrow band model called RGM3000 [4]. The scattering media are dealt with using the SHDOM solver [5].

2.2. Mascotte experimentation and simulations

A detailed experimental study was performed at the exhaust of the MASCOTTE test facility developed by ONERA. Several time-resolved in situ optical diagnostics obtained at high repetition rates were used to characterize the afterburning plume zone: stereoscopic particle image velocimetry (2D-3C PIV), laser induced fluorescence images of OH radical (OH-PLIF) and spontaneous emission images of excited OH*. The aerodynamics of the supersonic plume is visualized using the PIV measurements, and the afterburning zone is characterized through the OH-PLIF technique as well as the excited OH* emission measurements. A prototype fast Fourier transform spectroradiometer was used for recording infrared emission spectra at several locations in the plume. A medium-wave (3-5 µm) infrared camera and a short-wave (0.7-1.6 µm) infrared camera were set to get full images of the plume. More details about the experimental setup can be found in [6][7][8].

All the measurements were used to assess the numerical models of our code CEDRE [3], and our radiative transfer code (called SIR). In order to investigate the reactive plume structure and dynamics, a reactive Large Eddy Simulation (LES) was performed. Indeed, this simulation approach enables the description of the turbulent structures and their development in the exhaust plume. The final LES mesh contains 34 million of tetrahedral elements, and is only 1 m long and 0.1 m wide. The large eddy simulation was performed over 7 ms. The simulation was performed thanks to a GENCI (Grand Equipement National de Calcul Intensif www.genci.fr) allocation of 1 million CPU hours, on CEA’s Curie supercomputer. For more details about the MASCOTTE LES computation, please refer to [7][8][9][10].

A RANS (Reynolds-Averaged Navier-Stokes) simulation was also performed with CEDRE and compared to the LES calculations in order to quantify the error induced by the average turbulence model. The same chemical kinetic scheme was used for both LES and RANS computations. The RANS turbulence model used was k-epsilon modified for axisymmetry.

2.3. Infrared measurements and simulations for MASCOTTE campaign

The IR radiance cartography and the spectral intensity were computed for one snapshot extracted from the LES simulations and for the time-averaged flowfield, over the spectral band 2000-4000 cm-1 (2.5 – 5 µm). The radiative species considered are H2O, CO2 and CO. The radiative transfer code used is a Narrow Band Statistical Model based on Curtis-Godson approximation [11], which takes into account the spectral correlations in case of multiple layers of gas with different physical conditions. Figure 3 shows the spectrally-integrated radiance cartography for one snapshot (left) and for the RANS simulation (right). One can notice the turbulent eddies on the LES snapshot, whereas on the RANS simulated plume, the turbulence is averaged. More detailed analyses and comparisons can be found in [7][10].
3. TESTING CDSD-4000 DATABASE

3.1. CDSD-4000 database

Tashken et al. [1] released in 2011 a new version of Carbon Dioxide Spectroscopic Databank called CDSD-4000. The databank contains the line parameters (positions, intensities, air- and self-broadened half-widths, coefficients of temperature dependence of air- and self-broadened half-widths, and air-broadened pressure shifts) of the four most abundant isotopologues of CO2. The databank has 628,324,454 entries, covers the 226–8310 cm\(^{-1}\) spectral range and designed for the temperature range 2500–5000K. It was designed primarily for very high-temperature applications such as star atmosphere studies and planet atmosphere entries. It weighs 24 Gb. CDSD-4000 is freely accessible via the Internet site ftp://ftp.iao.ru/pub/CDSD-4000.

Currently, PRECISE radiative transfer code SIR uses HITEMP-2010 database [2]. HITEMP is a molecular spectroscopic database for high-temperature modelling of the spectra of molecules in the gas phase. It is analogous to the HITRAN [12] database (dedicated to atmospheric applications) but encompasses many more bands and transitions than HITRAN for the absorbers H2O, CO2, CO, NO, and OH. HITEMP-2010 contains 11,193,609 CO2 lines and weighs less than 2 Gb.

Figure 4 presents the line distribution for HITEMP-2010 and CDSD-4000 as a function of line intensity at reference temperature 296K. The graph evidences a cut-off above \(10^{10}\) cm\(^{-1}\)/(molecule cm\(^{-2}\)) for HITEMP-2010 line intensities, whereas CDSD-4000 line intensities go as down as \(10^{11}\) cm\(^{-1}\)/(molecule cm\(^{-2}\)) at reference temperature 296K. This means that CDSD-4000 encompasses lines that were considered negligible by HITEMP-2010: however, at very high temperatures, these lines may become significant.

Figure 5 presents the line distribution for HITEMP-2010 and CDSD-4000 as a function of the rotational quantum number J. HITEMP-2010 line distribution exhibits a lower centroid than CDSD-4000. This shows that CDSD-4000 lines can address higher energies applications than HITEMP-2010.

3.2. CO2 slab test-case

ONERA line by line (LBL) radiative code makes use of accelerating parameters in order to speed up the radiation computation. These parameters are computed for every line in the input spectroscopic database, prior to any radiative calculation. Their purpose is to estimate during the LBL radiation calculation of a specific medium if the line is significant or negligible. Details about their use and computation can be found in [13]. On spectral band 2000-2100 cm\(^{-1}\), the generation of the accelerating parameters lasted 2 days and 3 hours for HITEMP-2010 (400,000 transitions), 5 days and 16 hours for CDSD-4000 (19,000,000 transitions).

We then tested both the completed databases on a simple test-case: a slab of N2 gas with 1% CO2, at temperature 884K. This is a reference test-case shared in the framework of NATO technical group AVT-232 [14].

Figure 6 presents the radiation emitted by the slab of gas at 884K computed with both databases: 1 second for the LBL calculation with HITEMP-2010, 1 minute 26 seconds with CDSD-4000. The differences in the results are negligible. We then tried with a higher temperature: 2500K. Results are presented on Figure 7: there is a clear discrepancy between both databases for this higher temperature.
Figure 7: Spectral radiance (W/sr/cm\(^{-1}\)) as a function of wavenumber (cm\(^{-1}\)) for the CO\(_2\) slab (Temperature = 2500K): for HITEMP-20210 (blue) and CDSD-4000 (red)

3.3. Methane flame test-case

The next test-case was selected because we have high-resolution spectroscopic measurements to compare with simulations. In this test case, we considered a methane flame burning in the air. The combustion gases were CO, CO\(_2\), and H\(_2\)O, with a maximum temperature of 2210K. This hot flame is somehow representative of the temperature conditions and species that can be found in rocket exhaust plumes, at ground pressure conditions. The test case reproduced an experimental setup described in [15]. The numerical results were compared to the IR emission spectrum of combustion gases in a quasi-two-dimensional burner measured by a Fourier transform spectrometer. The spectra were convoluted to a spectral resolution of 5 cm\(^{-1}\) in order to simplify the comparison.

Figure 8: Comparison of the simulated spectral radiance convoluted at 5 cm\(^{-1}\) for HITEMP-20210 and CDSD-4000 with the measured spectrum

Figure 8 presents the comparison of the CDSD-4000 and HITEMP-2010 simulated radiances with the measured radiance of the methane flame. There is an obvious improvement of the radiance prediction with CDSD-4000 with respect to HITEMP-2010 in this spectral band. This is consistent with figure 2 of [1] which compares the observed and calculated emissivity of the CO\(_2\)+H\(_2\)O+CO+O\(_2\) mixture in the 4.3 µm region at 2850K with CDSD-4000 and HITEMP-2010 databases.

3.4. MASCOTTE test-case

Infrared instruments in MASCOTTE experiment included a high frequency spectrometer developed by ONERA Microspoc (2.5-5.2 µm) with a 2-cm diameter field of view. Microspoc aimed at two different locations during the trials: 23 cm and 75 cm from the nozzle exit plane, looking at the plume with an aspect angle of 90°. As you can see on Figure 9, which represents the temperature on the plume axis as predicted by the RANS simulation, both locations correspond to high temperature positions on the plume axis. The radiative simulations corresponding to both sensor positions were performed using ONERA LBL code with CDSD-4000 and HITEMP-2010 databases.

Figure 9: Temperature on the plume centreline for the RANS simulation

Figure 10: (Up) Comparison of the simulated apparent spectral radiance at 23cm from the nozzle plane for HITEMP-20210 and CDSD-4000 with the measured spectrum, (Down) Discrepancy between CDSD and HITEMP LBL results
Figure 11: (Up) Comparison of the simulated apparent spectral radiance at 75cm from the nozzle plane for HITEMP-20210 and CDSD-4000 with the measured spectrum. (Down) Discrepancy between CDSD and HITEMP LBL results

Figure 10 and Figure 11 compare the numerical results simulated with both databases with respect to the measured spectra. We have a very good agreement for both simulations at 23cm from the nozzle plane: the discrepancy between both numerical results is limited. This is mainly because the maximum temperature on the sensor line of sight is below 2000K: HITEMP database is thus as well suited for this case as CDSD-4000. The agreement is a little less good at 75cm from the nozzle plane. We have a higher discrepancy between both simulations on spectral band 2000-2100 cm⁻¹. The maximum predicted temperature on this line of sight is about 2150K: this higher temperature may account for a better prediction of the spectral intensity with CDSD-4000 especially on this spectral band.

4. CONCLUSION

CDSD-4000 is a very “heavy” database, with more than six hundred million lines only for CO₂. It requires a very long processing to compute accelerating parameters for LBL calculations and long LBL calculations. It enables to predict CO₂ emitted radiation with a greater precision than HITEMP at high temperature, especially on spectral band 2000-2100 cm⁻¹, which is a band of interest for early warning systems. This was demonstrated on two simple test cases in this paper. However, when applied to a full plume, the benefit seems less evident, because the line of sight crosses temperature gradients from low (atmospheric) temperature up to high temperatures where CDSD-4000 efficiency is proven. These temperature gradients lower the interest of using CDSD-4000 for infrared signature prediction. The main inconvenient of CDSD-4000 can however be overcome if this database is used to compute band model parameters. Actually, when simulating the radiance of the full plume such as on Figure 3, we seldom use LBL calculations, which are too much time-consuming. We use a Narrow Band Statistical Model based on Curtis-Godson approximation [11]. This model uses parameters that were fitted on numerous LBL calculations performed on a homogeneous medium. With the same methodology, we could compute band model parameters from CDSD-4000 database, which would reproduce the good precision at high temperatures. A preliminary step would be to make a selection of the more significant lines for our application in order to reduce the delay to compute the band parameters. This task will be performed in project SIMBA2.

5. PERSPECTIVE: PROJECT SIMBA2

Project SIMBA2 has started in 2021 for 4 years to study supersonic reactive and turbulent plumes for signature applications. It is divided in two main parts. The first part deals with the study of post-combustion (reheat) as a function of altitude and speed. It will feature trials in wind tunnels and in a vacuum tank, with corresponding LES and RANS simulations. The second part will tackle the problem of the plume in rarefied atmosphere, with chemical and radiative disequilibria. Dedicated simulation tools will be developed and tested.

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7. REFERENCES


