High Fidelity Model for Self-sustained Oscillations in Heated Jets

S. Demange* and F. Pinna.†
Von Karman Institute for fluid dynamics, Rhode-Saint-Genese, 1640, Belgium

U. Ali Qadri‡ and M. Juniper.§
University of Cambridge, Cambridge, CB2 1PZ, United Kingdom

The effect of property modelling on the stability features of heated axisymmetric jets is investigated by comparing the results of unsteady simulations and spatio-temporal Linear Stability Theory (LST) analyses obtained with three different models of Thermodynamic and Transport Properties (TTP). Two of these models are commonly found in the literature and assume respectively constant properties and a Calorically Perfect Gas (CPG) assumption, while the third model is a novel approach for this kind of study as it considers a mixture of gases in Local Thermodynamic and chemical Equilibrium (LTE) accurate up to extreme temperatures. Each model is implemented in a DNS code already used in the literature for jet stability analyses, and the LST computations are carried out in the VKI Extensible Stability and Transition Analysis (VESTA) toolkit. The LST analysis is performed on the steady state obtained from DNS simulations using a Selective Frequency Damping (SFD) method.
Results show that the choice of property model has a significant impact on the development of self-sustained oscillations through changes of the absolute region length. Variable properties introduced in the CPG and LTE model have a amplifying effect on absolute instabilities downstream of the inlet. However, the modification of temperature profiles in LTE is found to strongly damp absolute instabilities at high temperatures. Cases with a long enough absolute region are found to support global modes, which are investigated with a Fast Fourier Transform (FFT) method.

Nomenclature

α	streamwise wavenumber	p	pressure
θ	momentum shear thickness	Pr	Prandtl number
λ	thermal conductivity	q	generic flow quantity
ρ	density	q_∞	quantities in ambient flow
μ	viscosity	q_j	quantities at inlet centerline
ω	angular frequency	r, θ, z	cylindrical co-ordinates
D	jet diameter	R	jet radius
Ec	Eckert number	Re	Reynolds number
f	dimensional frequency	S	ambient-to-jet temperature ratio
h	static enthalpy	S_1	ambient-to-jet density ratio of [1]
i	imaginary number ($i^2 = -1$)	T	temperature
m	azimuthal integral wavenumber	u, v, w	velocity components along r, θ, z

*PhD candidate, Aeronautics and aerospace department, simon.demange@vki.ac.be
†Senior research engineer, Aeronautics and aerospace department, fabio.pinna@vki.ac.be
‡Leverhulme Early Career Fellow, Department of Engineering, uaq20@eng.cam.ac.uk
§Professor of Thermofluid Dynamics, Department of Engineering, mpj1001@eng.cam.ac.uk

I. Motivation

Heated jets are flow structures found in many aerospace and industrial applications where the control of the transition to turbulence is an important design factor, for example to enhance mixing after gas injectors or to minimize the level of noise in a facility. In environments with extreme temperatures, such as plasma wind tunnels, the contribution of complex flow Thermodynamic and Transport Property (TTP) models on the jet stability features is expected to be non-negligible, and yet remains to be examined.

Low-density jets are known to act as oscillators to external perturbations and to support self-sustained periodic oscillations once the ambient-to-jet temperature ratio S is lowered below a critical value. The occurrence of these *global modes*, as shown by Lesshafft et al. [2], was correlated early on by Monkewitz and Sohn [3] to the absolute nature of instabilities found with the local Linear Stability Theory (LST), and experimentally confirmed by Monkewitz et al. [4]. Several studies, including the work of Lesshafft and Huerre [5], Juniper [6, 7], Balestra et al. [8], have consequently used parametric analytical jet profiles in order to identify configurations yielding absolute instabilities. Among them, Lesshafft and Huerre [5] identified the baroclinic torque as the underlying mechanism behind the transition from convective to absolute instabilities in axisymmetric heated jets without counter-flow.

Most of the previously cited studies rely on simplified models of the flow TTPs. A common assumption is to consider a constant viscosity and thermal conductivity throughout the jet profiles [5, 9]. However, the centerline-to-ambient viscosity ratio found with Sutherland's law for a jet with $S = 0.15$ is approximately 3.33, which is expected to have some influence on the stability at low Reynolds number. More recent work [10] use a temperature power law to obtain the viscosity, and a constant Prandtl number for the thermal conductivity under the Calorically Perfect Gas (CPG) assumption. Nonetheless, this model cannot describe accurately flows for temperatures above 800 K [11]. Therefore, the present work compares results obtained with the two previously mentioned models (constant properties and CPG) against stability computations assuming the flow as a mixture of perfect gases in Local Thermodynamic and chemical Equilibrium (LTE). This latter model being the simplest available for temperatures above 2000 K [11].

As highlighted by Coenen et al. [10], the study of one-dimensional analytical profiles allows flow parameters to be varied independently and imposes shapes not necessarily representative of real configurations. By considering the more physically sound boundary layer integration as their base state, their analysis obtained different values of the critical parameters promoting absolute instabilities. The effect of profile shapes were also investigated by Lesshafft and Marquet [12], showing that absolute instabilities might arise in uniform density jets by deforming the velocity profile shapes. Thus, realistic base states are obtained in the present work by computing the downstream evolution of the flow from initial top-hat profiles. Another justification for the use of such base states was found in the comparison of LST studies against Direct Numerical Simulations (DNS) and experimental observations by Lesshafft et al. [2], Nichols et al. [9], Coenen and Sevilla [13], showing that a long enough absolute region is necessary to trigger self-sustained oscillations. If such is the case, the oscillations frequency should be close to the absolute frequency of the profile located at the upstream boundary of this region [2]. Here again, different property models are expected to change the streamwise evolution of the mean flow, and potentially the length of the absolute region.

The objective of the present work is to asses the influence of different TTP models on the stability of axisymmetric heated jets. To this end, the DNS code developed by Nichols [1] has been modified to include the same property models as in the stability analysis including: constant properties, CPG and LTE. Spatio-temporal LST computations are performed on the steady state obtained by means of Selective Frequency Damping (SFD) similarly to Qadri et al. [14]. Stability results are then compared against a Fast Fourier Transform (FFT) analysis of the unsteady simulations at the same parameters.

II. Formulation

A. Base state

The base states investigated are obtained by the injection of an initial streamwise velocity $\bar{w}$ and temperature $\bar{T}$ profile into a resting fluid of the same gas at a temperature T_∞. The flow is axisymmetric and is described with the cylindrical coordinates (r, θ, z) respectively denoting the radial, azimuthal and streamwise directions. The inlet profiles at $z = 0$ are described with the classical top-hat expressions corresponding to the profile number 2 from Michalke [15]. Velocity profiles are characterized by their ratio of radius over momentum shear layer thickness R/θ, and a Reynolds number based on the inlet centerline velocity U_j and jet diameter. The radial velocity at the inlet is $\bar{v} = 0$. Jets studied are in the low Mach number regime, thus the viscous heating is neglected and the inlet temperature profiles take the same shape as the velocity ones. The injected gas temperature is controlled by the centerline-to-ambient temperature

ratio $S = T_\infty/T_\mathrm{j}$, where T_j is the inlet centerline temperature.
The evolution of the flow downstream of the inlet is described with the low Mach number approximation of the Navier-Stokes equations, allowing for density variations while neglecting pressure waves. These equations are solved in the DNS code of Nichols [1] and were modified according to the property models described in II.B. Effects of the buoyancy are neglected and a single species of gas is considered. Therefore, the mixture fraction equation described by Nichols [1] is not used. Flow quantities are rendered non-dimensional using the jet diameter D as reference length and U_j as reference velocity. The reference density is chosen in the outer flow ρ_∞ for all models and the non-dimensional temperature is scaled as $T = (T_\mathrm{dim} - T_\infty)/(T_\mathrm{j} - T_\infty)$ for the constant property and CPG models. Other reference quantities are taken at the inlet centerline. Classical non-dimensional numbers indicated in Nichols [1] are defined using the centerline inlet quantities, which may vary with different models.
Two cases are investigated, assuming the parameters given in table 1. Both inlet profiles display a thin shear layer, and are in the absolutely unstable region given by Lesshafft and Huerre [5] for constant properties. The first case is chosen to highlight the influence of variable properties, while the second is chosen to showcase high temperature effects. All computations are computed on a 255×513 grid, for a domain extending to respectively 4 and 20 jet diameters. Boundary conditions for the simulation and the Selective Frequency Damping method used are the same as the ones described by Qadri et al. [14]. The convergence to a steady state is also helped by injecting a small coflow (1% of U_j) in the domain.

Case	Re_D	S	R/θ
1	400	1/7	20
2	225	1/15	20

Table 1 Main parameters of the inlet profiles defining the two test cases investigated.

B. Property models

The constant property model (TTPcst) relies on the same equations than Nichols [1], considering a constant viscosity $\mu = \mu_\infty$ and thermal conductivity $\lambda = \lambda_\infty$, while a unit Prandtl number is assumed.

The CPG model introduces variable properties to the flow. The viscosity is obtained with Sutherland's law, while the thermal conductivity is retrieved from a constant Prandtl number $\mu c_\mathrm{p}/\lambda = 0.7$ and a constant isobaric specific heat is $c_p = 1004.5$ J kg^{-1} K^{-1}. Modifications have been introduced in the energy and momentum equations to take into account the temperature derivatives of μ and λ.

The LTE model allows high temperature effects to be considered, considering the flow as a mixture of perfect gases in equilibrium. The mixture used in the present work is an 11 species air mixture (N, O, NO, N_2, O_2, N^+, O^+, NO^+, N_2^+, O_2^+, e^-) allowing for ionization effects. Under the equilibrium assumption, a single temperature is needed to describe the flow and chemical reactions are assumed to happen instantly. This results in the same equations as for the CPG model, chemistry effects being fully contained in the variations of the TTPs due to the (seemingly) instantaneous adaptation of the flow composition with variations of pressure and temperature. However, the energy equation is expressed in terms of static enthalpy h for convenience, and a low Eckert number expansion is assumed due to the ambiguous nature of the Mach number in equilibrium. Some reference quantities are also changed with respect to the CPG case. Details of the LTE implementation in the DNS are available in Demange et al. [16], and the resulting non-dimensional equations are:

$$\frac{\partial \rho}{\partial t} + \nabla(\rho u) = 0, \tag{1a}$$

$$\nabla p^{(0)} = 0, \tag{1b}$$

$$\frac{\partial(\rho u)}{\partial t} + \nabla(\rho u u) = \nabla p^{(1)} - \frac{1}{S_1 Re}\nabla(\tau), \tag{1c}$$

$$\rho\frac{Dh}{Dt} = \frac{1}{S_1 Re Pr}\nabla(\lambda \nabla T). \tag{1d}$$

With,

$$S_1 = \frac{\rho_\infty}{\rho_\mathrm{j}}, \quad Re = \frac{\rho_\mathrm{j} u_\mathrm{j} D}{\mu_\mathrm{j}}, \quad Pr = \frac{\mu_\mathrm{j}}{\lambda_\mathrm{j} T_\mathrm{j}} \frac{p_\infty}{\rho_\infty} \text{ and } \quad Ec = \frac{\rho_\infty u_\mathrm{j}^2}{p_\infty}, \tag{2}$$

where Ec is the Eckert number, and the indices $^{(0)}$, $^{(1)}$ denote the order of approximation used in the low Eckert expansion for the pressure terms, similarly to Nichols [1] in the low Mach number approximation. Within the LTE assumption, the density ratio S_1 can no longer be approximated as the inverse of the temperature ratio $1/S_1$. Furthermore, the coupling of equation (1b) with steady pressure lateral boundary conditions imply that $p^{(0)}$ is constant. The current implementation takes advantage of this fact by interpolating the TTPs from pre-computed tables over the temperature field during the DNS routine assuming a constant static pressure. A constant pressure value of $p_\infty = 100$ mbar is considered in order to approach conditions where the equilibrium assumption has been verified experimental by Cipullo et al. [17] in the VKI plasma wind tunnel. At such low pressure, the continuous regime assumption has been checked by computing the Knudsen number $Kn = l/L_\mathrm{ref}$ at the centerline for the temperature ratio studied. The mean free path $l = \mu/p_\mathrm{s}\sqrt{0.5\pi RT/M_\mathrm{w}}$ is computed assuming LTE, with $R = 8.3144$ J mol^{-1} K^{-1} the universal gas constant and M_w the mixture molecular weight at temperature T and static pressure p_s.
Finally, the temperature profile at the inlet is also modified in LTE in order to obtain a more realistic shape. The top-hat analytical expression is imposed on the static enthalpy using an enthalpy ratio equivalent to the temperature ratio S imposed with other models. The temperature inlet is then retrieved by inverting the enthalpy-temperature table computed assuming LTE.

III. Stability analysis

Stability equations are obtained from the fully compressible Navier-Stokes equations, assuming small perturbations $q' = [u', v', w', T', p']$ around the base state denoted $\bar{q}$. The automatic derivation of the equations is done in the VKI Extensible Stability and Transition Analysis toolkit [18, 19]. Additional grouping terms specific to high temperatures described by Malik and Anderson [11] are added to the LTE equations. Following the classical LST assumptions: $q' \ll \bar{q}$ is assumed and perturbations are expressed as the normal modes of the flow given by:

$$q'(r, \theta, z, t) = \tilde{q}(r) e^{i(\alpha z + m\theta - \omega t)} + c.c. \tag{3}$$

With α and m being respectively the streamwise and integral azimuthal wavenumbers, while ω denotes the angular frequency and "$c.c.$" the complex conjugate. In this process, perturbations of the transport properties are also considered by expanding:

$$\mu' = \frac{d\bar{\mu}}{d\bar{T}} T' + \frac{d\bar{\mu}}{d\bar{P}} p' \tag{4}$$

according to the TTP model used to compute the base state. Stability equations along with suitable boundary conditions reduce this to a generalized eigenvalue problem solved on stretched Chebychev-Gauss-Levy points in VESTA similarly to Demange et al. [16]. The absolute nature of instabilities is investigated by examining the sign of the spatio-temporal growth-rate ω_i at saddle points of ω in the complex wavenumber plane (α_r, α_i) according to the Briggs-Bers criterion.

IV. Results

A. Effects of properties in the base states

An overview of the inlet profiles and steady flow fields obtained with the DNS is given in figure 1a for the first case with $S = 1/7$ and in figure 1b for the second case with $S = 1/15$. For both jets, the inlet velocity profiles are identical with the three models of properties, but, the downstream evolution and inlet temperature profiles differ according to the model used. Due to the different procedure used to obtain the temperature profile in LTE, the resulting thermal layer is pushed away from the center with respect to the shear layer position. This effect is expected to damp absolute instabilities due to the lowering of the baroclinic torque. As expected, differences between the LTE and other model temperature profiles are more pronounced as the temperature ratio is decreased. Additionally, LTE temperature profiles exhibit humps associated with dissociation reactions in the flow influencing the temperature-enthalpy relation.

Downstream of the inlet, each property model yields a significantly different evolution of the flow. Assuming constant properties returns a faster decreasing centerline velocity and temperature due to the under-estimation of the flow thermal conductivity and viscosity. However, results depend on the range of temperature studied. For the first jet case

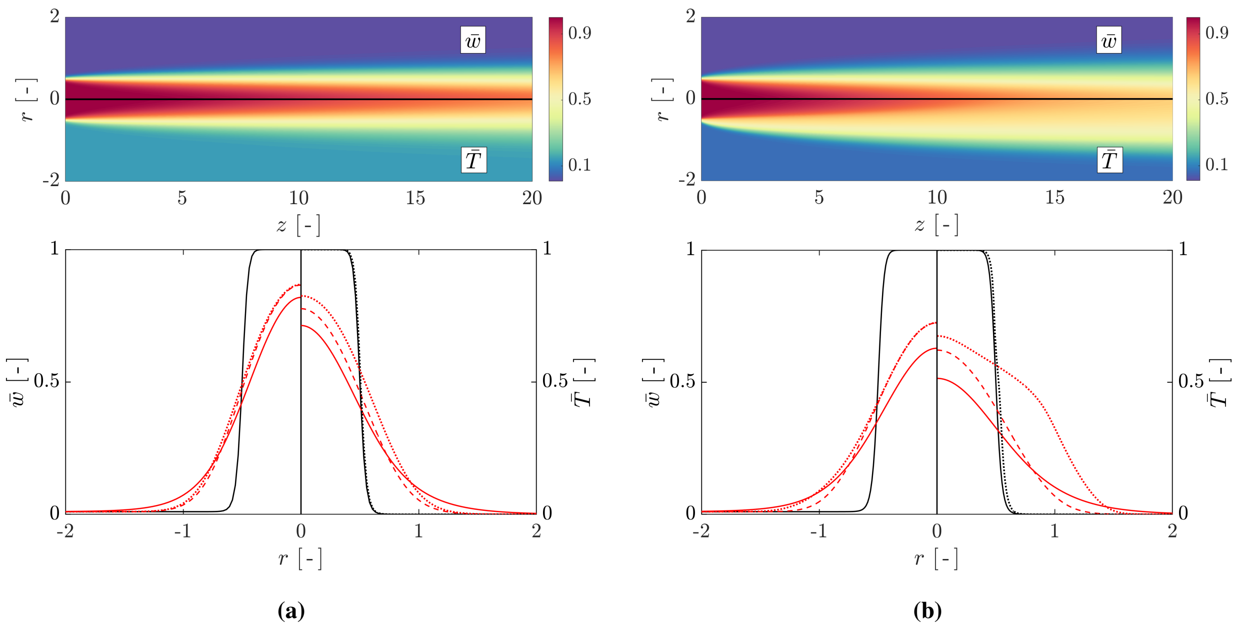


Fig. 1 Base states obtained for the two jet cases: (a) $S = 1/7$, $Re = 400$ and (b) $S = 1/15$, $Re = 225$. The contour plots are obtained with the LTE implementation of the DNS code. Profiles of velocity and temperatures are displayed at $z = 0$ (*black*) and $z = 15\,D$ (*red*) for the three models: TTPcst (——), CPG (- - - -) and LTE (· · · · · ·).

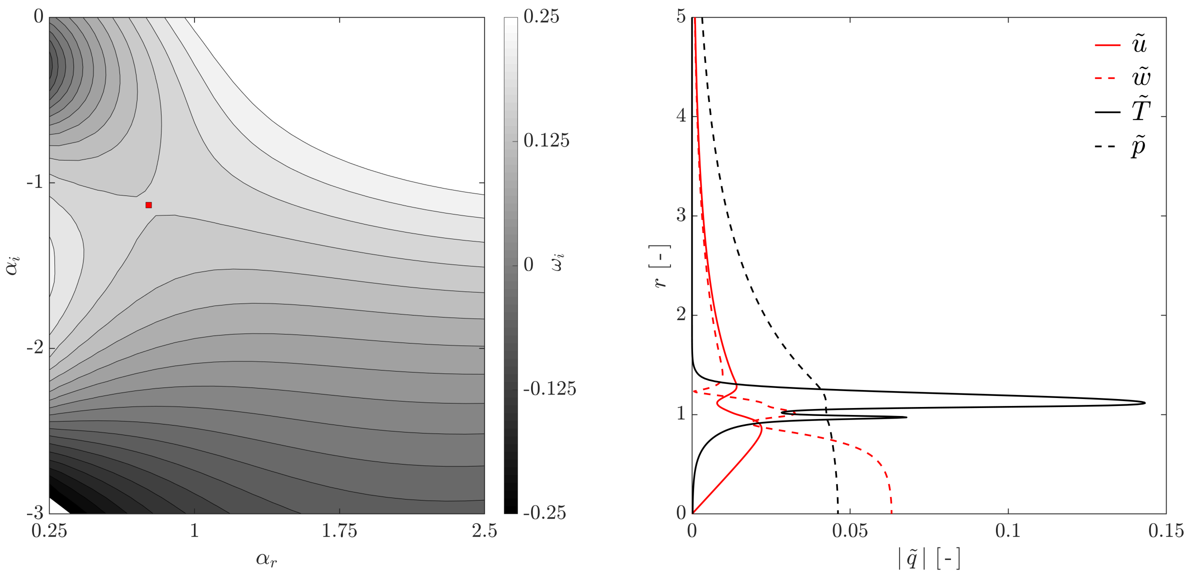
with $S = 1/7$, the introduction of variable flow properties is found to sharpen the gradient of temperature and velocity in the radial direction, leading to a configuration favoring absolute instabilities [12]. Although the velocity profiles of the CPG and LTE model are similar in this case, temperatures above 2000 K are enough to yield a different thermal conductivity for these models and a different temperature field. In the second case, where temperatures reach 5250 K, differences between models are more visible. In particular, the LTE model yields a thicker thermal layer than the CPG and TTPcst ones, moved further away from the shear layer. Although the equilibrium model still yields the lowest temperature ratio at any given streamwise position, its peculiar profile shape is expected to be more stable.

B. Stability results

The current spatio-temporal analysis is carried out on the base state described in the previous section, and is restricted to $m = 0$ as axisymmetric jet-column modes are expected to prevail for jets with thin shear layers [5]. Contours of the spatio-temporal growth-rate $\text{Imag}(\omega) = \omega_i$ are obtained by tracking the least stable mode along the complex wavenumber plane.

For each jet case and model studied, the spatio-temporal analysis done at the inlet shows the presence of a saddle point similar to the one displayed for the CPG model in figure 2a. These saddles are valid for the Briggs and Bers criterion as they are formed by the intersection of two α-branches issued respectively from the positive and negative halves of the wavenumber plane. For each case investigated and model, the absolute growth-rate at the inlet is positive, confirming the super-critical nature of the profiles injected in the domain. Details of the stability results at the inlet are given in table 2. Shapes of the perturbations associated with the saddle point are displayed in figure 2b for the case with $S = 1/15$ in LTE, and display pressure perturbations typical of the jet-column mode described by Lesshafft and Huerre [5]. For this particular case, the LTE temperature eigenfunction $\tilde{T}$ displays an additional peak at the position where a hump is visible in the temperature profile $\bar{T}$.

Saddle points are then tracked along the streamwise direction, and the resulting curves of absolute growth-rate are plotted in figure 3a for case 1 and in figure 3b for case 2. As expected, the length of the absolute region $l_{\text{ac}} = z(\omega_i > 0)$ is strongly dependent on the property model used. In the first case, the inlet absolute growth-rates for the three assumptions are relatively grouped due to identical velocity and similar temperature profile shapes. However, the TTPcst model predicts a shorter absolute region than the other models. Both the LTE and CPG model display a region of absolute



(a) **(b)**

Fig. 2 Examples of stability results: (a) Contours of the spatio-temporal growth-rate ω_i obtained at the inlet from the LST for the first jet case with the CPG model. (b) Absolute value of the perturbation shapes at the saddle point for the second jet case in LTE.

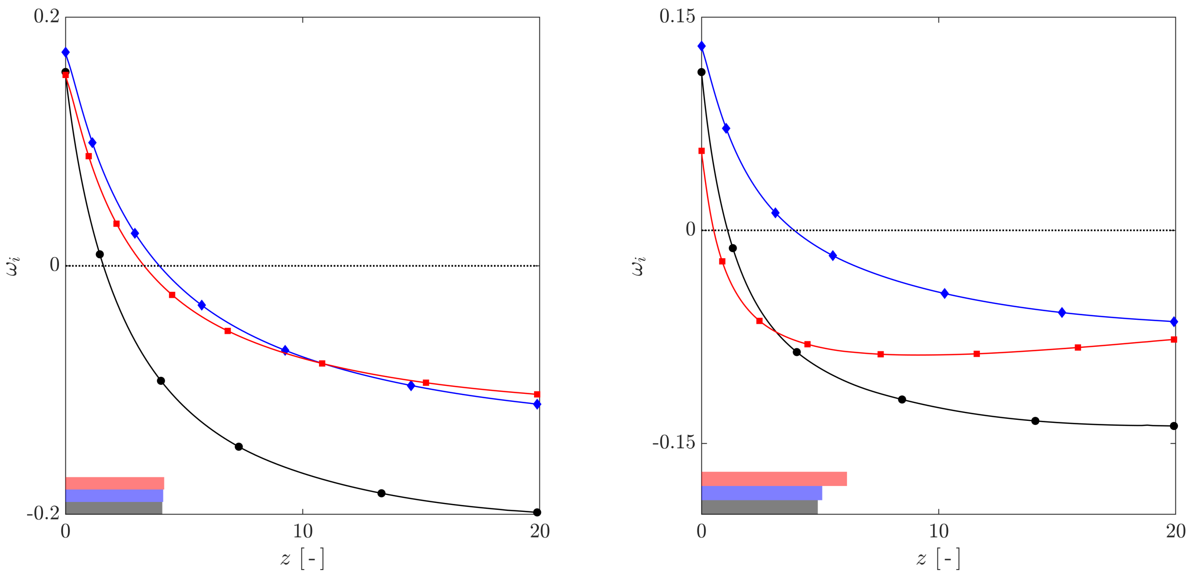
instability of the order of the the inlet absolute wavelength $\lambda_0 = 2\pi/\mathrm{Real}(\omega)$. These results indicates that introducing variable properties amplifies absolute instabilities in heated jets. Consequently, the CPG and LTE models are expected to support a global mode, while the TTPcst jet should remain globally stable [13]. For the second case with $S = 1/15$, differences between the models are once more amplified by extreme temperatures. The LTE and TTPcst models show much shorter absolute regions than the CPG model, and noticeably shorter than their respective inlet absolute wavelengths. For this case, differences between the LTE and CPG models are explained by the growing offset between the temperature and shear layers in LTE as the streamwise position increases. Such effect are much less pronounced in the case with $S = 1/7$. For $S = 1/15$, only the CPG case is expected to sustain a global mode. However, at such temperatures the LTE model should be closer to physical situations, and it can be considered that the CPG model largely overestimates the absolute instability influence on the flow.

	ω_0			λ_0 [-]			l_{ac} [-]		
Case	TTPcst	CPG	LTE	TTPcst	CPG	LTE	TTPcst	CPG	LTE
1	0.562 + 0.156i	0.546 + 0.172i	0.529 + 0.154i	4.08	4.12	4.16	3.19	7.91	6.63
2	0.335 + 0.111i	0.317 + 0.13i	0.215 + 0.056i	4.9	5.09	6.13	2.20	7.81	1.03

Table 2 Results of the LST analysis for the two jets studied at $z = 0$.

C. Global modes from DNS

The time evolution of the jets is investigated by setting the gain of the selective frequency damping to zero in the DNS. A non-dimensional time step of $\Delta t = 0.005$ is imposed during the simulations, which leads to different dimensional times for the different models, thus the analysis is done in non-dimensional terms. Unlike the study of Lesshafft et al. [2], it was found that no injection of disturbances is necessary to trigger the global modes of the flow in the present case. This is believed to be due to the implicit excitation applied by the initialization procedure, which



(a) **(b)**

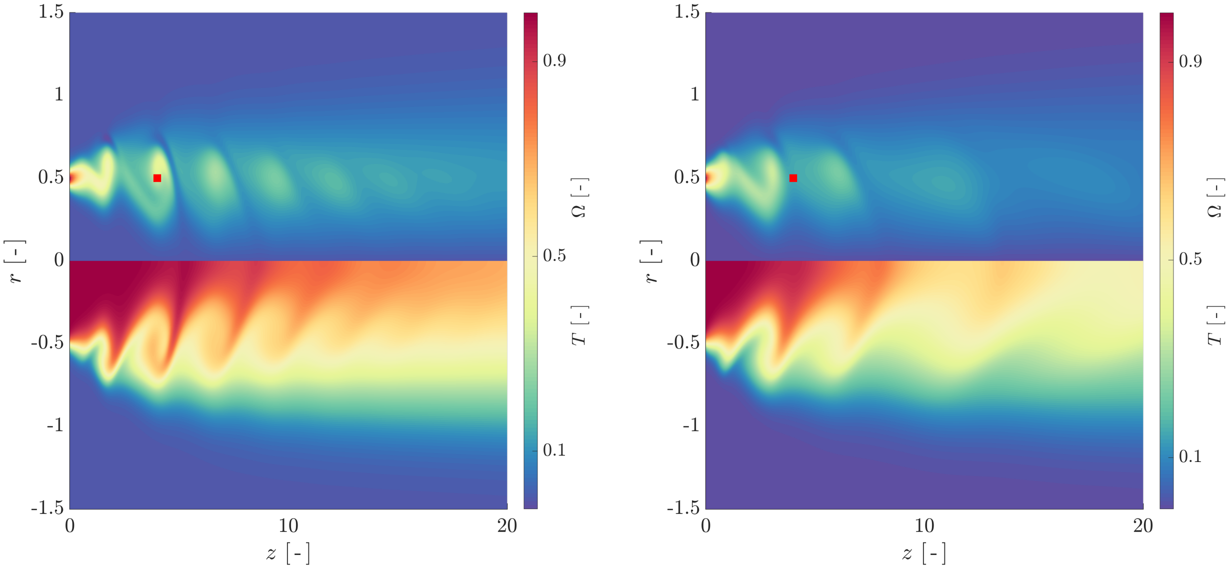
Fig. 3 Streamwise evolution of the absolute growth-rate obtained from the LST for (a) the $Re = 400$, $S = 1/7$ and (b) the $Re = 225$, $S = 1/15$ jets, for each model: constant properties (*black* ○), CPG (*blue* ◊) and LTE (*red* □). The inlet absolute wavelength with each model is also indicated by a rectangle of the corresponding color.

consists of imposing the super-critical inlet profiles throughout the domain. After this initial step, a transient phase is observed, which is followed by the growth of coherent structure.
In the first jet case, both the CPG and LTE models show such structures, while they only appear with the CPG model for the hotter case with $S = 1/15$. With the other property models, simulations converge toward the steady state after a few oscillations are detected. Example for both jet cases of the instantaneous vorticity $\Omega\,(= \partial v/\partial z - \partial w/\partial r)$ and temperature fields obtained with the CPG model are presented in figure 4 after the transient phase. As already pointed out by Lesshafft et al. [2], results of time accurate simulations imposing the axisymmetry of the jet may promote the development of rolled up vortices near the shear layer that would be highly unstable in a fully three-dimensional flow. Therefore, the long-time development of these structures in the present simulations is non-physical. However, the initial growth of these structures is believed to be physical as absolute instability modes observed in section IV.B are axisymmetric. Observations of the rolled up vortices displayed in figure 4 are coherent with observations of Lesshafft et al. [2].

The time analysis of the flow is carried out by probing the time evolution of the density field in the shear layer, at $z = 4\,D$ after the inlet and $r = 1/2\,D$. This position is marked by a red square in figure 4 and is on the path of the vortices. In cases were a periodic regime is reached, data is sampled every 100 time steps for a total of 100 thousand iterations, which is enough to obtain a satisfying spectral accuracy. In cases where only a transient phase is observed, the sampling frequency is increased to identify the initial oscillation frequency. The time evolution of the density is plotted in figure 5b with each of the three models for the first jet case. In the second jet case, the LTE and TTPcst model converge towards the steady state without displaying significant oscillations. For the other cases, regular patterns can clearly be identified. These observations are in good agreement with predictions from the LST analysis.

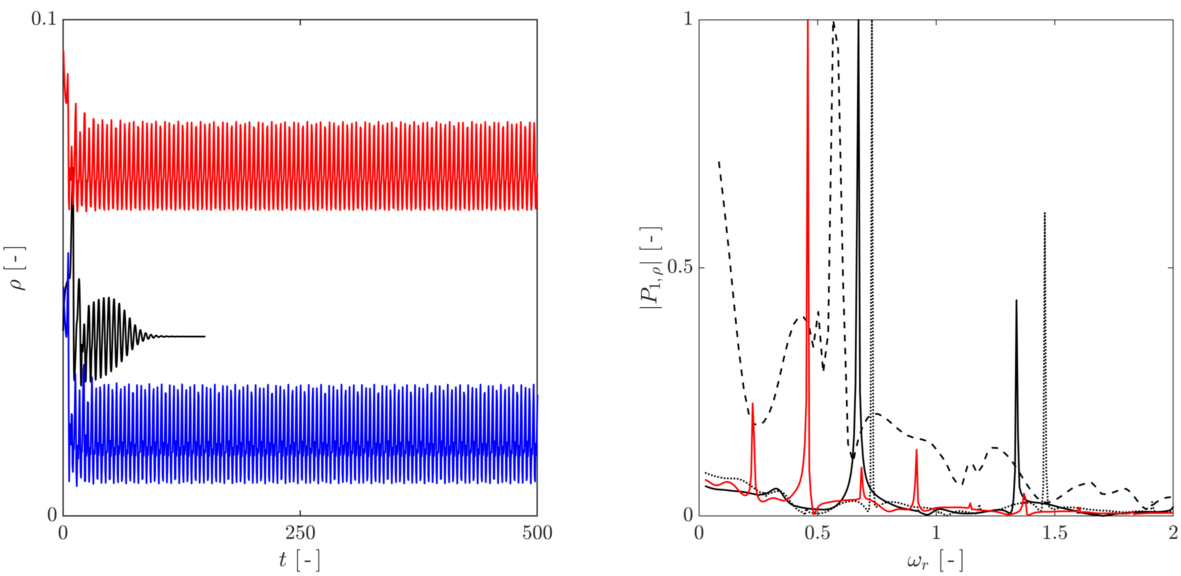
For cases where oscillations are identified, a Fourier analysis of the probed unsteady density is carried out to compare frequency against LST ones. This analysis is performed by computing the single-sided amplitude spectrum of signals plotted in figure 5a with the MATLAB® *fft* routine. Non-dimensional frequencies are then scaled to use the same reference length as the stability analysis: $D/2$. The resulting spectra are displayed in figure 5b. Spectra of the FFT analysis show a clear peak for each case studied. The presence of harmonics is found for jets sustaining global modes, and is not observed in the first jet case with the constant properties model. Results are summarized in table 3.

Current results show an large discrepancy between LST and FFT frequencies (between 20% and 30%) for super-critical cases supporting a global mode, in agreement with observations of Lesshafft et al. [2]. The precision of the



(a) **(b)**

Fig. 4 Instantaneous flow vorticity Ω (up) and temperature T (down) field for the CPG jets with (a) $S = 1/7$, $Re = 400$ and (b) $S = 1/15$, $Re = 225$ at iteration 50000, after the transient phase. A red square marks the position where the time evolution of the flow is probed.



(a) **(b)**

Fig. 5 Results from the unsteady simulations: (a) Temporal evolution of the density at $r = 1/2\,D$ and $z = 4\,D$ for the $S = 1/7$ $Re = 400$ jet case with the TTPcst (*black*), CPG (*blue*) and LTE (*red*) models. Values are shifted up and down for visibility. (b) Normalized FFT one-sided power spectrum based on the density evolution in case 1 (*black*) for the TTPcst (- - - -), CPG (——) and LTE (······) models, and in case 2 (*red*) for the CPG model only. The spectrum is given in terms of the non-dimensional frequency based on the jet radius to match LST.

Test	$\omega_{\mathrm{r,\,LST}}$ [-]			$\omega_{\mathrm{r,\,FFT}}$ [-]		
	Cst	CPG	LTE	Cst	CPG	LTE
1	0.562	0.546	0.529	0.5864	0.7288	0.6723
2	0.335	0.317	0.215	-	0.4587	-

Table 3 Comparison of the non-dimensional frequencies ω_r obtained with the LST and FFT analyses. The symbol "-" is used when no distinct frequency is identified.

frequency prediction does not seem to depend on the property model used. However, for the first jet with constant properties, the prediction is improved up to a 4% error, as such case is closer to to the occurrence of a global mode.

V. Conclusions

The effect of different property models on the stability of super-critical heated jet flows has been investigated using a Fourier analysis on unsteady simulations and the numerical solution to the one-dimensional spatio-temporal LST problem. Results show a strong influence of the thermodynamic and transport property modelling on the stability features of the jets studied. In the cases investigated, the integration of variable properties in the base state computation and stability analysis is found to strongly amplify absolute instabilities downstream of the inlet. However, in more extreme environments with sufficiently low temperature ratios, the modification of temperature profiles obtained with an equilibrium model accounting for chemical reactions are found to quickly damp absolute instabilities when compared against a Calorically Perfect Gas model. The choice of property model is thus found to influence the occurrence of self-sustained oscillations in heated jets by influencing the length of the absolute region starting at the inlet. These results are confirmed with unsteady simulations, where the development of a global mode is observed in cases where the absolute length is approximately the same as the absolute wavelength at the inlet, in agreement with Coenen and Sevilla [13]. A good agreement is found between the frequencies obtained from the LST and Fourier analyses in the case of a constant property model, as the global mode only appears in the transitent regime following the initialisation. This agreement however deteriorates for strongly oscillating jets obtained with the CPG and LTE models, in agreement with observations of Lesshafft et al. [2] for super-critical conditions.

Acknowledgments

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