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Phenomenological Aerodynamic Analysis of an Ejector Exposed to Large Inlet Pulsations

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Fig. 6

a) Time-averaged transverse velocity gradient $\partial \bar{U}/\partial y$ and b) normalized vorticity thickness δ_ω of bottom and top shear layers for OP1-Exp.

Assuming constant specific heat capacities between primary and secondary flow, a convective Mach number $M_c = (u_{sec} - u_{pri})/(a_{pri} + a_{sec})$ is defined for the configuration. For the studied operating point OP1 with $M_c = 0.29$, indicating that shear layer growth can be approximated by an incompressible approach [39]. With $K_u = \bar{u}_{sec}/\bar{u}_{pri}$ and $K_\rho = \bar{\rho}_{sec}/\bar{\rho}_{pri}$, the spatial vorticity thickness growth rate for an incompressible shear layer is given by an empirical correlation [40]:

$$\left(\frac{\partial \delta_\omega}{\partial x}\right)_{\rho-const.} = 0.165\frac{(1-K_u)\sqrt{1+K_\rho}}{2\sqrt{1+K_\rho K_u}}. \tag{14}$$

For OP1-Exp, Eq. (14) predicts a theoretical vorticity thickness growth rate for an incompressible mixing layer of 0.0524. The actual vorticity thickness growth rate averaged between $0 \leq x/d_{nozzle} \leq 3.5$ and that averaged between top and bottom shear is 0.0589, hence overestimating the ideal incompressible growth rate by roughly 12%. In light of the goals of this study, this result is deemed acceptable and confirms that shear layer development is sufficiently captured in the computation.

B. Analysis of Novel Operating Point Representative of RDC Exhaust

As shown in previous sections, a suitable computational setup for the ejector has been obtained. In order to study its behavior when subjected to pulsating flow, the operating point OP2-U (see Table 1) is implemented.

1. General Flowfield Description

To describe the unsteady flowfield, a single period of the pulsation is analyzed. The absolute time of the simulation is normalized by the convective time t_c, which refers to the time that a hypothetical weightless particle would require to be convected from the primary inlet to the outlet. For OP2-U, $t_c = 8.2 \times 10^{-3}$ s.

Figure 7 shows instantaneous static pressure fields for a single period ($t/t_c = 2.927$. Fig. 7a. to $t/t_c = 3.018$. Fig. 7f), where the black line represents an isoline of $\mathbf{Mach} = 1$. As expected, the nozzle exit velocity regime is periodically changing between subsonic and supersonic. At $t/t_c = 2.927$, the primary flow is choked but becomes subsonic shortly after the nozzle throat, whereas in the second half of the mixing chamber, a pressure wave is evident. Shortly after, at $t/t_c = 2.945$ (Fig. 7b), the flow unchokes completely in the primary nozzle, leading to an entirely subsonic domain. The pressure wave has moved upstream, following the reduction in primary inlet pressure. At $t/t_c = 2.963$ (Fig. 7c), a new pulse is introduced while the pressure wave has continued its upstream movement. After the interaction with the supersonic jet ($t/t_c = 2.981$, Fig. 7d), the pressure wave is located further downstream than in the previous snapshot. Soon after, a secondary shock forms at the mixing chamber exit ($t/t_c = 3.000$, Fig. 7e). With the pressure retracting, the shock strength diminishes ($t/t_c = 3.018$, Fig. 7f) and it eventually moves upstream as a pressure wave again, completing the periodic process.

Fig. 7

Instantaneous static pressure fields with a black isoline of $\mathbf{Mach} = 1$ for six snapshots (a–f), corresponding to a single pulsation period for OP2-U.

The appearance of the secondary shock and the pressure wave observed in Fig. 7 requires further investigation. Thus, in the following, an attempt is made to track this movement visually using density gradient magnitude fields. Figure 8 shows a time-space diagram of the secondary shock/pressure wave over a single period (the same period as shown in Fig. 7), complemented by five snapshots of the density gradient magnitude with an isoline of $\mathbf{Mach} = 1$. The first time instant shown corresponds to $t/t_c = 2.927$ (i.e., to Fig. 7a), where the pressure wave is located at $x/d_{noz} \approx 10$ in an entirely subsonic mixing chamber. The pressure wave then moves upstream until it impinges the supersonic jet at $t/t_c = 2.972$ and $x/d_{noz} = 3.3$ (bottom left). Subsequently, the pressure wave breaks up into two parts as the entering supersonic flow hinders any further upstream displacement in the primary flow section of the channel. One part convects downstream with the incoming pulse; this part has been tracked in Fig. 8. This pressure wave now starts dissipating in the flow, and the last instant where the pressure wave is still slightly visible is $t/t_c = 2.990$ at $x/d_{noz} = 6.3$ (bottom right), although its surface is much more corrugated than before the interaction with the incoming jet. The other part of the pressure wave continues its upstream movement in the secondary, subsonic portion of the mixing chamber until it is evacuated at the secondary inlet boundary (not shown in Fig. 8). For $2.990 < t/t_c < 2.999$, there is neither a secondary shock nor a pressure wave visually evident in the domain (dashed black line in the time-space plot). However, for $t/t_c > 2.999$, a shock eventually forms at $x/d_{noz} = 12$ (top right in Fig. 8) that has been observed previously. The shock remains at its position until $t/t_c = 3.027$. Upon this point, upstream pressure starts decreasing again, and the periodic process repeats itself.

Fig. 8

Time-space diagram of the discontinuity observed for OP2-U, with zoomed views of the density gradient magnitude over an isoline of $\mathbf{Mach} = 1$.

In Fig. 9, the primary nozzle exit, secondary nozzle exit, and outlet mass flows are plotted over time. The resulting local entrainment ratio, denoted as ω_e is illustrated on the right ordinate. The applied frequency of 1 kHz (refer to Table 1) is accurately captured for the primary flow, with discernible mass flux amplitudes of approximately ±60% from the mean value. The obtained mass flux fluctuations are larger than in a typical RDC exhaust case (see, e.g., Ref. [41]) as a result of the studied conventional circular ejector configuration with a relatively small nozzle exit cross section compared to annular, existing RDCs. The pulsation of the primary flow introduces a perturbation in the entrainment of the secondary flow. In comparison to the primary flux, the pulsation amplitude of the secondary flow is relatively low. Consequently, the peaks in entrainment ratio primarily arise from the presence of small primary mass flow rates during fully unchoked, subsonic operation. The outlet mass flux pulsation frequency seems unchanged with respect to the primary nozzle exit, whereas the amplitude of the fluctuations is decreased significantly. A detailed analysis of fluctuation dampening throughout the device is presented in Sec. III.B.4. The time-averaged entrainment ratio was $\bar{\omega} = 2.126$ in this case. Compared to classical ejector operating conditions, where $\omega < 1.2 - 1.3$ [9], this value is significantly elevated, which is coherent with experimental and numerical studies of RDC–ejector interaction [6, 15].

Fig. 9

Integrated primary ($\dot{I}_{sec}$) and secondary ($\dot{I}_{pri}$) mass fluxes at the nozzle exit, outlet mass flux ($\dot{I}_o$), and local entrainment ratio $\omega = \dot{m}_{sec}/\dot{m}_{pri}$.

2. Instantaneous Velocity Profiles

Figure 10 shows instantaneous axial velocity profiles for five different axial stations between $0 \leq x/d_{noz} \leq 12$ (Figs. 10a–10e). The profiles are normalized by the time-averaged primary nozzle exit velocity $\bar{u}_{pri}$. At $x/d_{noz} = 0$, the maximum fluctuation amplitude of roughly 150% occurs between $t/t_c = 2.957$ and $t/t_c = 2.988$, which is coherent with previous observations at this time instant. The velocity profile for $t/t_c = 2.988$ changes its shape from a single maximum on the jet centerline (bell shape) to two symmetrical maxima located on the boundary between primary jet and secondary flow between $x/d_{noz} = 0$ and $x/d_{noz} = 1$ (Figs. 10a and 10b), a result indicating that the ejector behaves as a classical ejector at this time instant [11]. Further downstream at $x/d_{noz} = 3$ (Fig. 10c), this profile characteristic is not observed due to mixing between both flows. While the axial velocity for $t/t_c = 2.988$ reduces significantly throughout the mixing chamber from a maximum of $u/\bar{u}_{pri} = 2$ (Fig. 10a) to $u/\bar{u}_{pri} \approx 0.7$ (Fig. 10e), at time instant of $t/t_c = 2.957$, the axial velocity changes only between $0.8 \leq u/\bar{u}_{pri} \leq 1.8$ along the mixing chamber. At both other time instants, $t/t_c = 3.018$ and $t/t_c = 2.927$, axial velocity changes throughout the domain are within the limits of both other time instants evaluated. At $x/d_{noz} = 12$, the influence of the secondary shock is evident for $t/t_c = 3.018$ (Fig. 10e). Interestingly, the velocity profiles seem to align relatively well over time at $x/d_{noz} = 8$ (Fig. 10d). The result suggests that the ejector is capable of dampening the primary flow fluctuations to a certain extent and doing so on an axial distance shorter than the total ejector length of the investigated configuration, both of which are considered generally favorable for gas turbine integration.

Fig. 10

a)–e) Instantaneous velocity profiles between axial planes $x/d_{noz} = 0$ and $x/d_{noz} = 12$ during a single fluctuation period for OP2-U.

3. Kinetic Energy Dissipation

Second law analysis is an appropriate tool to assess losses in available work through turbomachinery components [42]. A detailed loss analysis and, as a consequence, a minimization of these losses is a crucial step in ensuring adequate performance of an RDC-ejector configuration, as mentioned in Sec. I. Without mass transfer and chemical reactions in the system, and neglecting any coupling effects, the irreversible entropy generation rate reads [43]:

$$\dot{S}_{gen} = \frac{\lambda}{T^2}\left(\frac{\partial T}{\partial x_i}\right)^2 + \frac{\tau_{ij}}{T}\frac{\partial U_i}{\partial x_j} \tag{15}$$

The kinetic energy and heat transfer loss terms $\mathbf{II_{KE}}$ and $\mathbf{II_{TE}}$ can be derived by a multiplication of both sides in Eq. (15) with the temperature. In an LES context, the SGS contributions need to be considered, which leads to the following form for both loss terms [42]:

$$\mathbf{II_{TE}} = \frac{\lambda + \lambda^{SGS}}{T}\left(\frac{\partial T}{\partial x_i}\right)^2 \tag{16}$$

$$\mathbf{II_{KE}} = \frac{1}{2}\left(\mu + \mu^{SGS}\right)\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} - \frac{2}{3}\frac{\partial U_k}{\partial x_k}\delta_{ij}\right)\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) \tag{17}$$

As pointed out by Inhestern et al. [44], heat transfer losses in adiabatic flow are irrelevant for the shaft power generation in the turbine. In addition, a volume integration of both terms revealed that $\mathbf{II_{TE}}$ is an order of magnitude lower than $\mathbf{II_{KE}}$, which is coherent with literature [45]. As a consequence, $\mathbf{II_{TE}}$ is not further considered in the remainder of the work.

In Fig. 11, a 2D map of $\mathbf{II_{KE}}$ and respective profiles along the ejector mixing chamber and diffuser are shown for OP2-U, where time averaging of $\mathbf{II_{KE}}$ was performed over 25 periods. As evident from Fig. 11a, for $x/d_{noz} < 12$, losses concentrate in the boundary layer and the shear layer, which is clearly visible as a loss source downstream of the nozzle exit. The secondary shock, located at $x/d_{noz} = 12$, introduces additional losses. In an attempt to quantify the relative loss contribution of the secondary shock, the region around $x/d_{noz} = 12$, where the shock is located in the time-averaged solution, was isolated from the rest of the domain. Subsequently, $\mathbf{II_{KE}}$ was volume integrated in the isolated region and in the entire ejector (excluding the primary inlet channel up toward $x/d_{noz} = 0$). Results showed that the secondary shock has only a minor influence on $\int \mathbf{II_{KE}} \cdot dV$, with a value of roughly 3%. Further downstream, flow separation in the diffuser increases $\mathbf{II_{KE}}$ at the wall and in the jet centerline in the region $12 < x/d_{noz} < 19$. Figures 11b–11i show eight axial cuts of the kinetic energy loss along the mixing chamber and diffuser. The development of the shear layer and the concentration of losses within it is clearly evident. For both $1 < x/d_{noz} < 3$ (Figs. 11b–11d), losses in the shear layer are at least as high as in the boundary layer. Outside of the shear layer and the boundary layer, losses are minimal at these axial positions. At $x/d_{noz} = 6$ (Fig. 11f), the shear layer has disappeared (as also visible in Fig. 11a) and $\mathbf{II_{KE}}$ is roughly constant in the central region of the channel. The lowest centerline value of $\mathbf{II_{KE}}$ is attained at $x/d_{noz} = 12$ (Fig. 11h). As derived previously, flow separation in the diffuser then leads to another increase in losses at $x/d_{noz} = 16$ (Fig. 11i).

Fig. 11

a) Time-averaged 2D field of the loss in kinetic energy ($\mathbf{II_{KE}}$); and b–i) transverse fields of $\mathbf{II_{KE}}$ above a line trace along $y/d_{noz} = 0$ for OP2-U.

4. Unsteadiness Analysis

An important objective of an ejector placed between RDC and turbine is the dampening of RDC exhaust gas fluctuations, which are considered detrimental for turbine operation [7]. The parameter $D = (\Phi_{max} - \Phi_{min})/\Phi_{mean}$, evaluated over a single period of the fluctuation, where Φ is an arbitrary, time-dependent quantity and the indices **max**, **min**, and **mean** refer to time, allows the calculation of the dampening factor [7]:

$$\xi = \frac{D_{ne1} - D_3}{D_{ne1}} \tag{18}$$

The factor is applied between the nozzle exit at axial plane **ne1** and plane 3, which refers to the exit of the diffusing section (see Fig. 1). Instead of the ejector outlet at station 4 to remove any possible dampening effects related to decreasing mesh resolution. To obtain a single value in the nonuniform axial planes **ne1** and 3, the total pressure field has been mass-flow-averaged and the static pressure field area-averaged, which are appropriate averaging techniques [46]. The dampening factor ξ was then calculated for 15 single periods for both static and total pressure signals, and results were subsequently averaged. The metric revealed that the amplitude of total pressure fluctuations is reduced by about 85%, whereas the static pressure fluctuation amplitude is reduced by about 70% between the primary nozzle exit and diffuser exit. This result is consistent with experimental measurements in an RDC–ejector configuration [6]. Figure 12 shows the time-dependent evolution of mass-flow-averaged total pressure (Fig. 12a), a fast Fourier transform (FFT) of the same quantity (Fig. 12b), and the time-dependent evolution of area-averaged static pressure (Fig. 12c) at the primary nozzle exit plane (total pressure $P^{tot}_{noz,1}$, static pressure $P^{stat}_{noz,1}$) and diffuser exit plane (total pressure P^{tot}_3, static pressure P^{stat}_3). The quantities have been normalized by their respective time-averaged values. Figures 12a and 12c corroborate the results mentioned above for the dampening of total and static pressure fluctuations. The periodically appearing second peak in static pressure at the nozzle exit (visible, e.g., at $t/t_c \approx 2.2$, $t/t_c \approx 2.235$ in Fig. 12c) is a result of the unsteady shock diamond structure moving periodically through the nozzle exit (as also seen in Fig. 7). The total pressure pulsation at the nozzle exit is distributed over three harmonics, with a clear peak at the imposed frequency of 1 kHz. Throughout the mixing chamber and diffuser, the frequency spectrum is retained, as indicated by the peaks of the blue trace in Fig. 12b. The diffuser outlet pressure fluctuation amplitudes are considered much more favorable for turbine integration than the nozzle exit signal [47].

Fig. 12

Evaluation of total pressure (a, b) and static pressure (c) unsteadiness between primary flow nozzle exit and diffuser exit.

IV. Conclusions

A numerical study on the effect of axially pulsating inflow on a conventional ejector configuration has been conducted with the intent of installing such a device downstream of an RDC chamber. In the first stage of the study, a stationary operating point (OP1-Exp) was computed, which showed good agreement with available experimental data. The vorticity thickness growth rate of the shear layer in this case was within 12% of an empirical reference value. Subsequently, a completely new operating condition (OP2-U) was selected, where a sinusoidal axial inflow pulsation was imposed at the primary inlet boundary. The pulsation was chosen in a way that the primary nozzle throat periodically chokes and unchokes, generating a flow fluctuating between subsonic and supersonic velocity regimes at the nozzle exit, which is representative of an RDC exhaust. The effects of mean temperature, gas composition, and flow angle fluctuations were ignored.

An analysis of kinetic energy dissipation revealed that the boundary layer, the shear layer between primary and secondary flows, and the flow separation induced in the diffuser are among the main loss sources. Additionally, it was found that the unsteady operating condition leads to the periodic presence of a discontinuity, although it had only a minor impact on the volume-integrated kinetic energy dissipation. The presence of this discontinuity demonstrated that an unsteady approach is necessary to characterize RDC–ejector interaction. On the other hand, the ejector was capable of reducing approximately 70% of the static and 85% of the total pressure fluctuation amplitude, whereas the total pressure fluctuation frequency was equal between the diffuser outlet and the nozzle exit. Instantaneous velocity profiles showed that axial velocities align relatively well at an axial distance of $x/d_{noz} = 8$, which is about a third of the total ejector length downstream of the nozzle exit. These findings are considered favorable for RDC integration and showcase the potential of utilizing an ejector as an intermediate component between RDC and axial turbine. Future work should include the implementation of temperature effects, flow angle fluctuations, and gas composition in the RDC exhaust gas. Moreover, with a dedicated design study more adapted to pulsating flows, some of the previously mentioned loss sources and internal phenomena could probably be mitigated while retaining the dampening characteristics.

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Tables

Table 1 Boundary values imposed for the ejector computation with operating points OP1-Exp and OP2-U

	OP1-Exp		OP2-U	
Parameter	Initialization	Simulation	Initialization	Simulation
p_{t_P}, kPa	296.82	−−	210.0	−−
T_{t_P}, K	295	−−	295	−−
$\bar{u}_{t_P}$, ms^{-1}	−−	23.64	−−	23.07
T_{st}, K	−−	295	−−	295
A_{t_P}, ms^{-1}	−−	−−	−−	100
f_1, kHz	−−	−−	−−	1
P_{t_P}, kPa	97	97	117.37	117.37
T_{t_P}, K	295	295	295	295
P_{st}, kPa	117.37	117.37	117.37	117.37

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