SCHOOL OF ENGINEERING

The University of Warwick, School of Engineering

ES4F5 Engine Sub-System Assignment

Con-Di Nozzle

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Nomenclature

$\dot{m}$	=nozzle inlet flow rate
γ	=ratio of specific heats
R	=gas constant
a	=local speed of sound
A	=area
P	=pressure
V	=velocity
M	=mach number
T	=temperature
C_A	=angularity coefficient
C_V	=velocity coefficient
α	=angle of exit flow
C_{fg}	=thrust coefficient
NPR	=nozzle pressure ratio
ρ	=density

Subscripts

exit	=nozzle exit
amb	=ambient condition
7	=nozzle inlet
8	=nozzle throat
9	=nozzle exit
9i	=ideal velocity at nozzle exit
s	=isentropic

1.0 Introduction

The convergent-divergent nozzle (con-di nozzle) consists of the pairing of a convergent nozzle and a divergent nozzle used for propulsion in a jet engine. Con-di nozzles are normally used for aircraft requiring supersonic, high Mach number speeds [1] with large pressure ratios [2]. Therefore they are employed by military aircraft with higher speed demands as an increase in thrust is provided, improving the thrust to weight ratio but with the detriment of increased fuel consumption, weight and cost [1]. In this report the con-di nozzle functions will be analysed: pressure control for optimum performance, conversion of potential energy of exhaust gas to kinetic energy. Also focussing on thrust minus drag performance, variable geometry control, thrust vectoring and military applications. The state of art will be discussed by analysis of the propelling nozzle of the Lockheed Martin F-35B Lightning II STOVL variant with outstanding aerodynamic performance, stealth and supersonic speeds [3].

2.0 The function of a con-di nozzle

In the convergent section of a con-di nozzle the pressure decreases and the velocity increases, Bernoulli's principles. At the throat of the convergent nozzle the velocity increases until it reaches Mach 1 (local sonic velocity), this is the maximum limit on the velocity and the nozzle is considered choked. With the flow velocity constrained to the local speed of sound at the throat, further increases in energy are recognized as a build-up in pressure with static pressure increasing above atmospheric [2]. Consequently, within the divergent section, after the throat, the stored pressure and thermal energy is exchanged into kinetic energy significantly increasing flow velocity to greater supersonic speeds (M>1). The change in velocity of gas flow in a con-di nozzle can be represented by equation 1[4] below,

$$(1 - M^2) \times \frac{dV}{V} = -\frac{dA}{A} \tag{1}$$

The equation shows that when the flow is subsonic (M<1), an increase in area results in reduced velocity and when the flow is supersonic (M>1) the area change has the effect of increasing flow velocity. As shown by equation 2[5], displaying the thrust of the aircraft.

$$F = mV_{exit} + (P_{exit} - P_{amb})A_{exit} \tag{2}$$

With a greater exit velocity V_{exit} the thrust of the aircraft is increased. The thrust is also contributed to by the increase in upstream pressure in the chocked throat of the convergent nozzle in the form of pressure thrust from the increased pressure difference [2]. Con-di nozzles utilise this pressure energy to add velocity to the flow and therefore increase the thrust. Where simply convergent nozzles are used on civil aircrafts energy is wasted as the exhaust gas does not expand rapidly enough to achieve ambient pressure however with con-di nozzles expansion is achieved in the divergent nozzle as shown by figure 1.

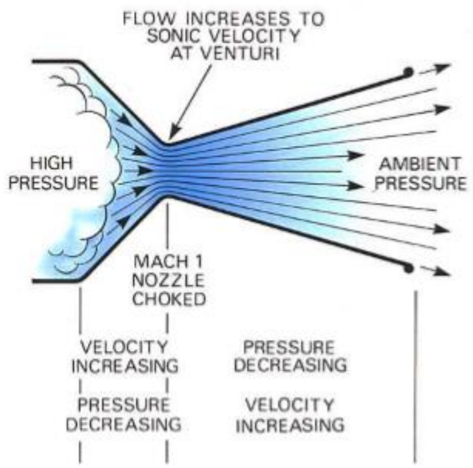

Figure 1 Supersonic airflow through a con-di nozzle [2]

3.0 Key requirements

Con-di nozzles are used in military aircraft therefore the key requirements are high speeds and the ability to operate over a wide range of operating conditions with comparably reduced importance on cost, efficiency and fuel usage. Figure 2 shows a simplified diagram of the station locations on a turbofan engine whereby a fraction of inlet air goes around the core engine section as shown the con-di nozzle has its inlet at 7, throat at 8 and divergent exit at station 9 [6]. The key design parameters are the area sizes at these station locations.

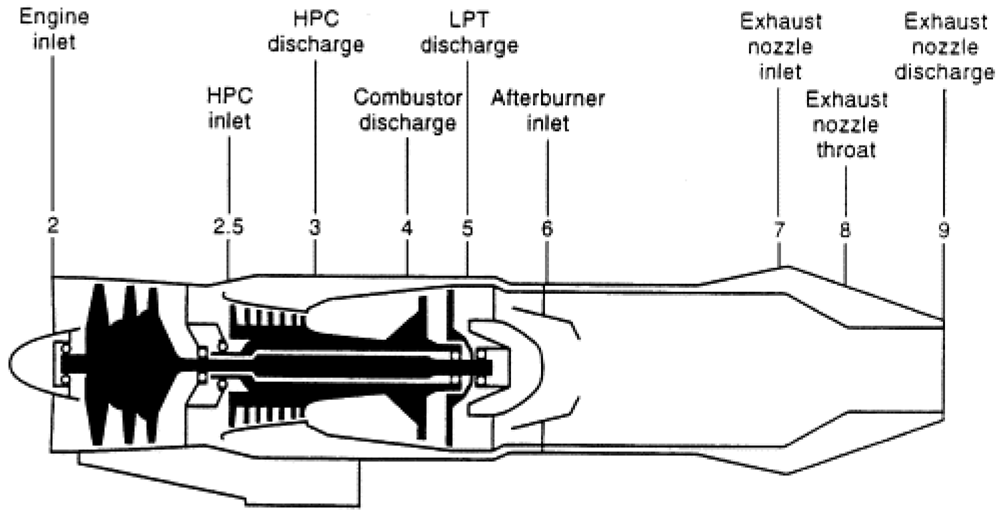

Figure 2 Engine station locations of a turbofan jet engine [6]

Nozzle sizing is critical as a correct balance of thrust, pressure and temperature is required, using a large nozzle will not maximise thrust however even though a small nozzle will improve these values, there is an increased risk of engine surge [2]. There are also key interdependencies within the engine, because the pressure increases in the compression processes must equal the decrease in pressure in the expansion processes for optimum efficiency [1]. The propelling nozzle areas impact this pressure change and so must be chosen with an understanding of the other subsystems.

3.1 Materials

For selection of materials when designing a con-di nozzle the temperatures in the jet engine must be considered. The temperature of gas flowing into the exhaust system is between 820K and 1125K and can be up to 2200K with afterburner use, which are common on military aircraft [2][1]. Afterburners can dramatically increase thrust by up to three times by burning fuel downstream of the turbine via fuel injectors and gutters [1]. With high temperatures comes issues with thermal expansion resulting in distortion and cracking, on top of this, heat transfer to the rest of the aircraft needs to be minimised. To deal with these conditions often materials including nickel and titanium are chosen due to their high-temperature characteristics [2]. As a consequence of expansion and contraction from temperature the mountings must be carefully designed to allow for these distortions.

3.2 Variable geometry

Military aircraft differ to Civil aircraft in many ways for example manoeuvrability is essential for fighter aircraft. For high manoeuvrability performance the aircraft must function correctly and efficiently over a much wider range of operating conditions which leads to the requirement of variable geometry con-di nozzles [1]. As already discussed, afterburners result in large increases in temperature and so the propelling nozzle throat area must have variable geometry to deal with the significant changes [1]. The temperature changes the local sonic velocity, $a = \sqrt{R\gamma T}$, where R is the molar gas constant, γ is the ratio of specific heats and T is the temperature[2]. The throat size is chosen in order to choke the flow and as a consequence of changing temperature and local sonic speed the throat area must be variable [4]. Area increases of up to 150% can be required for engines with afterburners fitted [7].

3.2.1 Nozzle pressure ratio

Nozzle pressure ratio (NPR) is the ratio of pressure over the nozzle, the con-di nozzle has to be designed so that the correct NPR is chosen for a particular operating condition as nozzle performance will be impacted [5]. Nozzle performance is measured by the ratio of actual thrust to ideal thrust [5] and so when the NPR is off design this will reduce. If the NPR is less than the required design point, the nozzle is said to be over expanded. Over expanded means that in the divergent section of the nozzle the flow expands to sub-ambient pressures, reaching ambient pressure before the exit station [8], resulting in drag, adding to the nozzle losses of the system [5]. Alternatively, when the NPR is too low, area ratio not high enough, the flow expands to a pressure greater than ambient [5].

3.2.2 Geometry control techniques

There are many different techniques for controlling the geometry of a con-di nozzle, the three techniques that will be focussed on include: geometrically scheduled, passively controlled and fully variable. Firstly, a geometrically scheduled area ratio is where the exhaust exit area, A_9 is kinematically linked to the throat area, A_8 [5]. The passively controlled area ratio technique is slightly more complicated where A_9 and A_8 are kinematically linked however a slotted mode strut allows different A_9 areas for a given A_8

[5]. The exit area is altered by internal pressure acting on the divergent nozzle flaps and has to be correctly balanced so that it moves to give the best expansion ratio for optimum performance [5]. Fully variable control is the most complex with the ability to vary A_8 and each divergent flap of A_9 ensuring the nozzle operates at peak performance and providing thrust vectoring [5]. Which technique is chosen, is determined by the weight, cost and mission type the aircraft is selected for. Geometrically scheduled is preferred if the mission consists of only a few known power settings as it is lighter and less expensive than fully variable but unlike fully variable, off-design the performance will drop [5]. Passively scheduling is a compromise between the two but verifying the pressure balance is critical to its performance [5].

3.3 Losses

Thrust performance is critical to a military aircraft and drag can seriously impact this and therefore must be considered in the design of a con-di nozzle. Key factors that will impact the drag are the mounting locations of the propelling nozzle and the cross-sectional area of the nozzle. Therefore, nozzles are commonly integrated into the aircraft to reduce the drag effect of external flow and also provide reduced radar detection for stealth purposes [5]. Seeing without being seen is an essential trait of a military aircraft and so stealth is a key factor in the success of the propelling nozzle design. The aircraft has to be designed to have a low radar signature in order to avoid detection[5].

Leakage losses occur in con-di nozzles affecting cavity air pressure level and the cooling airflow and even though leakage losses are generally less than 1% they still need to be accounted for in the design [7]. Due to the nature of variable geometry they are more vulnerable to leakage losses as more complex actuators and cooling systems are required. For example, a poorly scheduled cooling slot that provides film cooling can result in a pressure drop, effecting the thrust [7]. Other loss factors affecting the nozzle efficiency include nozzle friction impacting the boundary layer momentum (velocity coefficient, C_V) and loss due to nonaxial exit of exhaust gas (angularity coefficient, C_A). The angularity coefficient, also known as the divergence factor C_A is shown by equation 3 where α is the flow exit angle varying from the zero centreline [8]. C_V is a function of the wall Mach number, Reynolds number and nozzle surface area and the thrust coefficient is shown by equation 4 [7].

$$C_A = \frac{1 + \cos\alpha}{2} \tag{3}$$

$$C_{fg} = \frac{C_V C_A \frac{\dot{m}}{g}(V_{9i} + (P_9 - P_0)A_9)}{\frac{\dot{m}}{g} V_s} - \Delta C_{\substack{fg\ leakage \\ losses}} - \Delta C_{\substack{fg\ cooling\ air \\ throttling\ losses}} \tag{4}$$

4.0 Con-di nozzle specification

In this section of the report key anatomical dimensions are calculated and their effects discussed and analysed. Key parameters focussed on include inlet area A_7, throat area A_8, exit area A_9 and turbine entry temperature. For manual calculations the flow has been assumed to be ideal and isentropic and results have been validated and further analysed using computational fluid dynamics (CFD). Solidworks flow simulation CFD was used however for accurate CFD calculations a specialist would be advised. Many approximations were used for the CFD for example adiabatic walls and only considering the flow of air.

4.1 Sizing for speed requirements

4.11 Initial design

For the first design the characteristics of flow used were T_7=600K, $P_7 = 300kPa$, $V_7 = 300m/s$, $\dot{m} = 100\frac{kg}{s}$. The required speed of the flow on exit was a Mach number of 2. Firstly, from calculating the density of air at 35,000 ft (approximate operating altitude) under the set conditions the initial inlet area was calculated from equation 5, of the value $0.191m^2$. Then the Mach number was calculated from equation 6 where a is the speed of sound, γ is the ratio of specific heats assumed to be 1.4, R is the gas constant assumed to be 287 J/K/kg and T is the temperature and so T_7 was used. The Mach number is simply the ratio of the flow speed to the local speed of sound calculated, which was found to be 0.61.

$$\dot{m} = \rho AV \tag{5}$$

$$a = \sqrt{\gamma RT} \tag{6}$$

With the Mach number found, isentropic flow tables were used for γ=1.4 [9], to find both the stagnation temperature and stagnation pressure. Then using the fact that the nozzle design should have a Mach number of 1 at the throat of the nozzle, the tables were used to gain the pressure and temperature in the throat, P_8 and T_8. Next from the ideal gas laws, the density of the flow can be calculated as shown by equation 7.

$$\rho_8 = \frac{P_8}{RT_8} \tag{7}$$

With the density calculated and the speed found in the throat using equation 6 with T_8, equation 5 can be rearranged to find the area of the throat assuming mass flow rate is constant throughout. The area of the throat was calculated as $0.164m^2$. Finally, from the isentropic tables [9] the area ratio required for a Mach number of 2 is found to be 1.6875, which when multiplied by the area at the throat A_8, outputs the exit area required for the con-di nozzle A_9. To validate the manual calculations CFD was completed, displayed by figure 3. Approximate lengths from station 7 to 8 an to 9 were found in Ajoko et al [10]. Figure 3 shows that the flow starts around 0.6 Mach, achieving Mach 1 in the throat and reaching 1.8 Mach, close to the desired exit flow velocity requirement. The considerable acceleration of the flow is displayed by the velocity plot and the decrease in pressure towards atmospheric is shown via the pressure plot.

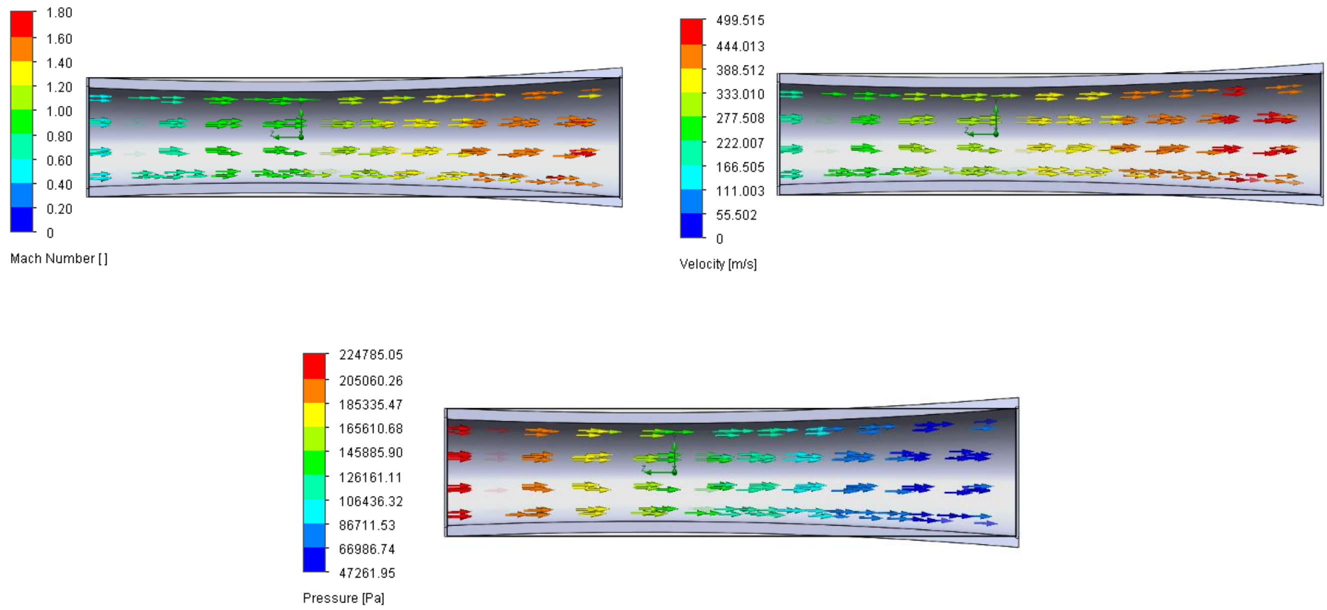

Figure 3 The Mach number, velocity and pressure CFD plots of the first design (M=2)

4.12 Second design

For the second design, the anatomical features were altered for the maximum speed requirements of the Lockheed Martin F-35 Lightning II which has a Mach 1.3 top speed [3] as this is a state of the art aircraft that utilises con-di nozzles. For a different Mach number, the area ratio of throat to exit area has to be changed and so using the isentropic tables a new area A_9 was found, $0.175m^2$ [9]. The CFD results are shown by figure 4, achieving an exit Mach of 1.38 slightly greater than the designed value. Figure 4 also displays the increasing velocity and reduction in pressure within the sub-system.

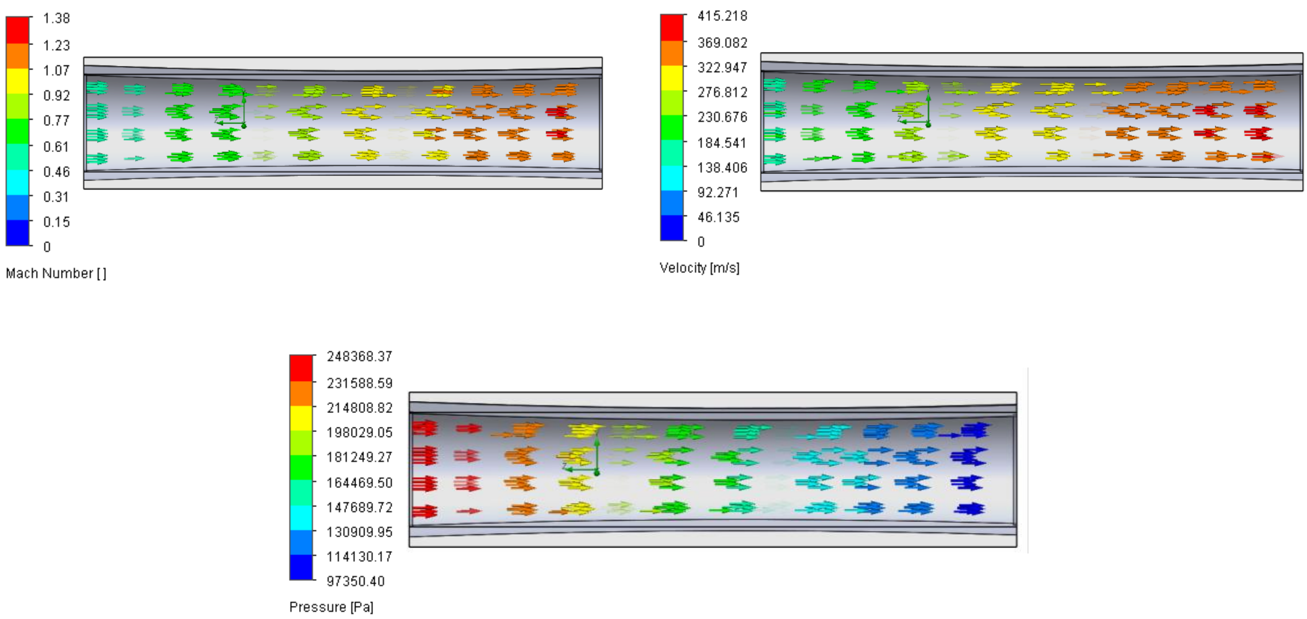

Figure 4 The Mach number, velocity and pressure for the second design (M=1.3)

4.2 Exit area parameter study

Using CFD it is possible to view the effect of varying different parameters representing different design choices. For the flow simulations in this section, the exit area A_9 was varied from the initial design area with radius 0.228m to an area with radius 0.3m to analyse the effect on exit flow speed. Figure 5 and 6 show the initial and final flow simulation results with the same Mach 1 at the throat but the design with the larger exit area reaching a larger Mach number. Table 1 displays the results from each iteration of the exit area change. This study highlights the need for correct sizing of the nozzle to achieve a desired performance/ speed for example for different operating conditions. Another outcome of this study is to show the need and development of variable geometry con-di nozzles as from changing the exit area radius from 0.228m to 0.3m resulted in a maximum Mach number increase from 1.58 to 2.25.

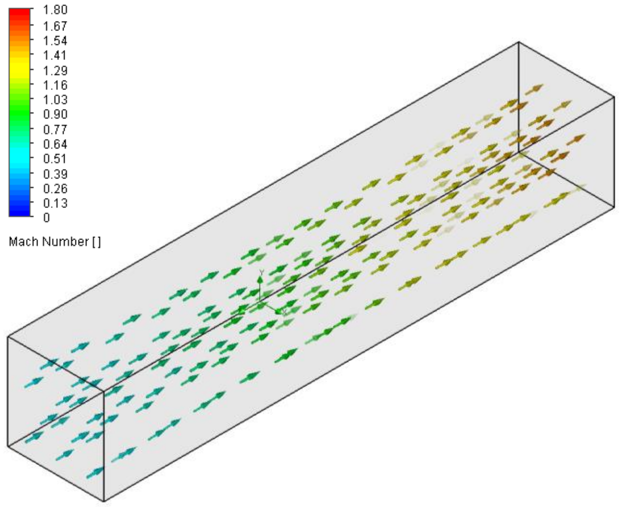

Figure 5 Mach number of exit flow with initial exit area

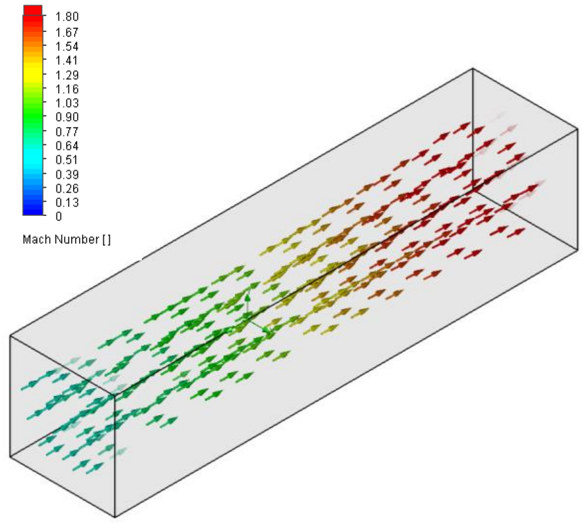

Figure 6 Mach number for final area size of study

Table 1 Results of parametric study of varying exit area

Parameter	1	2	3	4	5	6
Exit area radius m	0.228	0.236	0.260	0.284	0.292	0.300
Mach number	1.58	1.70	1.91	2.11	2.15	2.25

4.3 The afterburner effect

Another design choice of a military aircraft is the usage of afterburners and so a parametric study was completed to view the effect of increased inlet temperature on the exit velocity of the flow. Figure 7 displays the CFD model whereby an inlet area of $0.6m^2$ with inlet temperature of 600K. A military aircraft could have an increase from 913K without an afterburner to a temperature of 1542K using an afterburner, with a velocity increase with the square root of the temperature ratio [2]. From this study, with an increase in con-di nozzle inlet temperature T_7 from 600K to 1600K resulted in an exit velocity increase from 764.3m/s to 1143.6m/s, shown in table 2. Table 2 highlights the interdependency between the con-di nozzle and an afterburner, showing that afterburner effects must be considered with the nozzle design. These significant increases in flow velocity also show the need for variable geometry when an afterburner is used as the conditions rapidly change and therefore A_8 and A_9 must be varied to maintain optimum performance. To further improve the CFD simulations: increased boundary conditions would be applied, and method of characteristics would be used as in Ramji et al to design the shape of the con-di nozzle [11].

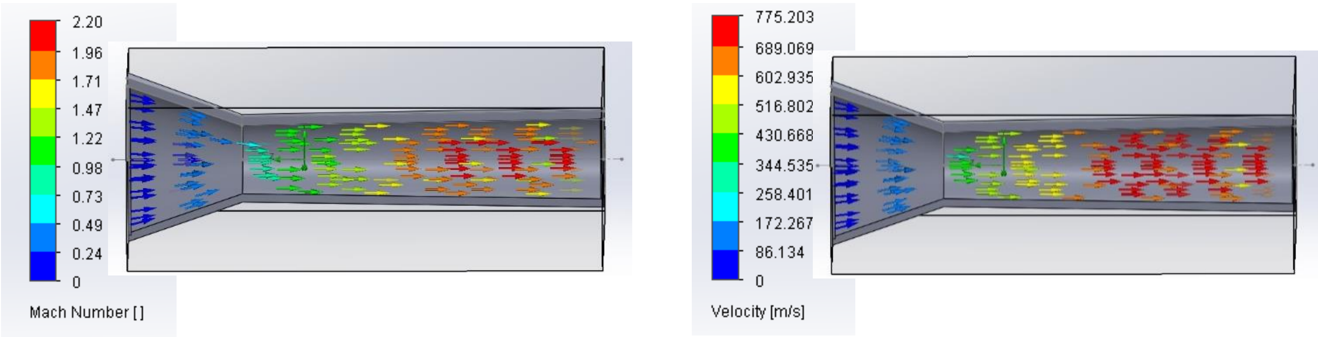

Figure 7 Mach number and velocity of flow simulation with inlet temperature 600K

Table 2 Maximum exit velocity of changed inlet temperatures

Parameter	1	2	3	4	5	6	7
Temperature (Inlet Mass Flow T_7) *K*	600	725	975	1225	1350	1475	1600
Exit velocity *m/s*	764.3	871.2	1030.5	1032.7	1062.9	1093.7	1143.6

5.0 State of the art

The existing state of the art use of a con-di nozzle can be found within the Lockheed Martin F-35 Lightning II, particularly the F-35B STOVL (short take off and vertical landing) variant. The F-35 uses a three bearing swivel module with a low observable axisymmetric nozzle (LOAN) that provides thrust vectoring [3]. This aircraft is the state of the art for minimising radar reflections by using serrated trailing edges as shown by figure 8, special coatings and reduced radar cross-section which were tested to evaluate their effectiveness, so the aircraft can see before being seen [3]. Through using a combination of thrust vectoring and variable geometry state of the art military aircraft can have improved manoeuvrability with the engine still able to operate optimally. By adding independent control of exit area A_9 to A_8 the EJ200 Eurofighter engine managed to see a 7% improvement for supersonic thrust through increased thrust and reduced nozzle drag [12].

One of most critical maintenance issues with con-di nozzles is the thermal degradation of the divergent section seals and flaps as they deal with high temperatures and large forces. To combat this issue, one of the main reasons for maintenance on modern jet engines, ejectors are utilised to provide effective film cooling by engine nacelle bay bypass air, reducing the nozzle temperature [3]. This reduces maintenance costs particularly with afterburner use due to the rapid increase in temperature, sufficient cooling is essential. However already mentioned, film cooling can lead to leakages and therefore reduced thrust so there is a compromise between maximum thrust and maintaining the structural integrity of the nozzle [7].

Figure 8 The propulsion system technologies of the F-35 [3]

5.1 Thrust vectoring

The three-bearing swivel module of the F-35 can move through 95 degrees, requiring no change in engine operation providing a large range of movement for thrust vectoring [3]. The yaw control this provides combined with the Rolls Royce shaft-driven lift fan system (figure 8) gives the aircraft the ability to hover and the option of STOVL, shown by figure 9 [3]. Thrust vectoring combined with variable areas are used in state-of-the-art military aircraft due to the benefits of sustained turning rate, enhanced performance, optimized angle of attack, increased safety, specific fuel consumption for more range etc [12]. Thrust vectoring of the con-di nozzles gives the aircraft the ability of reduced length take off and landings or even stalled take-offs and landings, allowing the use of aircraft carriers and improvised/ challenging runways [12]. The capability to actively control the aircraft while in stall (post-stall regime) gives significant advantageous in close combat or loss of control situations whereby there is aircraft failure or aerodynamic control damage [12]. Consequently, by potentially avoiding a complete aircraft failure the increased development and maintenance costs could be justified. There are different methods of thrust vectoring for example fluidic actuation which is an introduction of a secondary fluid and mechanical actuation involving hydraulic or pneumatics for altering the variable geometry con-di nozzle [12]. Even though thrust vectoring provides many benefits it also presents new challenges with the mechanical configuration consisting of components like the casing needed to allow the variable divergent nozzle area and direction. Another challenge is that the actuation system has to be adequate in delivering the required movements within the desired operating conditions [12].

Figure 9 F-35 B short take-off and landing [13]

6.0 Future trends

High temperatures and the increasing trend of complex variable-geometry leads to the need of improved, increasingly complex cooling techniques. Through increasing the amount of variability of the con-di nozzle the optimum operating condition range is increased but so too is the vulnerability to leakages and so there will be likely developments in aircraft technology to deal with this issue. For example, there may be improved versions of the tight gap and seam control found on the F-35 [3]. As used on the F-35 and an increasing number of fighter jets are innovative multifunctional nozzles providing variable geometry, thrust vectoring and thrust reversing. A likely future trend is the further increase in use of multifunctional nozzles delivering improvements in drag, weight, manoeuvrability and radar signatures [5].

Thrust vectoring is already utilised in military aircraft however developments of this technology is likely, and will improve the efficiency, weight of the systems and effectiveness of different fluidic vectoring techniques [5]. The further development and use of fluidic vectoring can improve the durability of the con-di nozzle as the number of moving parts in the nozzle are reduced [5]. Even though the technologies are available there may be issues with producing affordable solutions and so with further research and development the cost of technologies like thrust vectoring will decrease. The further development of extremely short take off and landing systems will give military aircrafts the ability to land in more extreme warzone terrain and a greater variety of military ships. Developments in materials science will also have a large impact on the future trends of con-di nozzle material selection. There is a need for materials with higher operating temperatures, low density, advanced cooling and ability to be fabricated, for example developments of carbon matrix composites [5].

7.0 Maintenance

Maintenance of a con-di nozzle is extremely important to ensure that the sub-system is in an airworthy condition and any work on the nozzle required is completed. Firstly, while in-flight different devices are used for measuring various parameters for example accelerometers for vibration, radiation pyrometers for temperatures measurements etc. Critically for a con-di nozzle is the measure of temperature overtime to give values for duration the aircraft is operating at high temperatures providing an indication of nozzle life [2]. A typical maintenance schedule of a jet engine would include a visual inspection of the exhaust system from the rear of the aircraft with a spotlight to look for issues and not exceeding the limit of 25 hours of flight time between inspections [2]. As already mentioned divergent nozzle flaps are vulnerable to thermal degradation [3] and so dimensional inspection considering fits and clearances is important for measuring the allowable distortion of the part and mating with other components [2]. Therefore, with more complex variable-geometry systems and cooling techniques, more mating clearances must be measured to ensure the systems still operate correctly.

Overhauls of the jet engine are completed to restore engines to full working order, clean, tune etc and the time between overhauls (TBO) is significantly shorter for military aircraft due to the dramatic temperature changes experienced. Another factor for TBO is the atmosphere the aircraft operates in, for example, in areas of high salt content the con-di nozzle would be more vulnerable to corrosion and at high altitudes there are more radioactive particles [2]. This shows the not just flight time completed should be used an indication of overhaul time. Thermal degradation of the con-di nozzle may lead to cracks developing. There are many different techniques for checking for cracks for example a fluorescent test using ultraviolet radiation, using coloured dye to enter cracks, magnetic crack testing and many more [2].

8.0 Conclusion

To conclude, in this report the effectiveness of a con-di nozzle has been analysed for developments of anatomical features. Facilitating the ability of military aircraft to reach supersonic speeds through increased exit velocity and pressure thrust, the nozzle is essential for high-speed mission requirements. Throat area and exit area of the nozzle have been calculated for desired exit velocity and varied to show the impact of geometry on performance. With a CFD study showing an increase in exit area radius from 0.228m to 0.300m delivering an increase in Mach number from 1.58 to 2.25 (table 1). The F-35 was analysed to show the development of variable geometry, afterburners and thrust vectoring con-di nozzles for maintaining optimum efficiency, improving speed and manoeuvrability. Through considering the requirements of a military aircraft con-di nozzle future trends have been hypothesised for reducing thermal degradation and improving efficiency.

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