VTU-NPTEL-NMEICT Project Progress Report

The Project on Development of Remaining Three Quadrants to NPTEL Phase-I under grant in aid NMEICT, MHRD, New Delhi

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<th>Subject Matter Expert Details</th>
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| Course Name: | Applied Thermodynamics |
| Type of the Course | web |
| Module | VII |

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MODULE-VII
COMPRESSIBLE FLOW & STEAM NOZZLES

QUADRANT-2

Animations
1) https://sites.google.com/site/mypapalexandris/animations-from-numerical-simulations/
2) https://archive.org/details/nasa_techdoc_20040086795
3) http://www.dynaflow-inc.com/Products/Software/2_3DynaFS/Compressible-Euler-3DynaFS.htm
4) http://www.slideshare.net/tamilaghil/modern-compressible-flow-by-jdanderson
5) http://www.authorstream.com/Presentation/aSGuest85656-825109-chapter-10-compressible-flow/
6) http://in.ask.com/youtube?q=youtubecompression&related+to+compressible+flows&v=GgQH/XrKufQ&qsrc=472
7) http://in.ask.com/youtube?qsrc=1&o=21395&q=compressible+flows&v=GgQH/XrKufQ&qsrc=472
8) http://in.ask.com/youtube?q=animation+related+to+steam+nozzle&page=2&qid=95A092CE6B67AFA3BBF26C5E2FF812CB&qsrc=1&o=21395&l=sem
9) http://in.ask.com/youtube?qsrc=1&o=21395&q=compressible+flows&v=GgQH/XrKufQ&qsrc=472

Videos:
http://in.ask.com/youtube?q=youtubecompression&related+to+compressible+flows&v=GgQH/XrKufQ&qsrc=472

http://in.ask.com/youtube?qsrc=1&o=21395&q=compressible+flows&v=GgQH/XrKufQ&qsrc=472

http://in.ask.com/youtube?q=animation+related+to+steam+nozzle&page=2&qid=95A092CE6B67AFA3BBF26C5E2FF812CB&qsrc=1&o=21395&l=sem

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http://in.ask.com/youtube?qsrc=1&o=21395&q=compressible+flows&v=GgQH/XrKufQ&qsrc=472
INTRODUCTION TO COMPRESSIONBLE FLOW

A compressible flow is that flow in which the density of the fluid changes during flow. All real fluids are compressible to some extent and therefore their density will change with change in pressure or temperature. If the relative change in density $\Delta \rho/\rho$ is small, the fluid can be treated as incompressible. A compressible fluid, such as air, can be considered as incompressible with constant $\rho$ if changes in elevation are small, acceleration is small, and/or temperature changes are negligible. In other words, if Mach’s number $U/C$, where $C$ is the sonic velocity, is small, compressible fluid can be treated as incompressible.

- The gases are treated as compressible fluids and study of this type of flow is often referred to as ‘Gas dynamics’.
- Some important problems where compressibility effect has to be considered are:
  (i) Flow of gases through nozzles, orifices;
  (ii) Compressors;
  (iii) Flight of aeroplanes and projectiles moving at higher altitudes;
  (iv) Water hammer and acoustics.

- ‘Compressibility’ affects the drag coefficients of bodies by formation of shock waves, discharge coefficients of measuring devices such as orificemeters, venturimeters and pitot tubes, stagnation pressure and flows in converging-diverging sections.

BASIC EQUATIONS OF COMPRESSIBLE FLUID FLOW

The basic equations of compressible fluid flow are: (i) Continuity equation, (ii) Momentum equation, (iii) Energy equation, and (iv) Equation of state.

INTRODUCTION TO NOZZLE

A nozzle is a flow passage of varying cross-sectional area in which the velocity of fluid increases and pressure drops in the direction of flow. Thus in nozzle the fluid enters the variable cross section area duct with small velocity and high pressure and leaves it with high velocity and small pressure. During flow through nozzle the enthalpy drops and heat drop in expansion is spent in increasing the velocity of fluid. Similar to nozzle a duct with variable cross-section area will be called diffuser if the fluid gets decelerated, causing a rise in pressure along the direction of flow. Nozzles are generally used in turbines, jet engines, rockets, injectors, ejectors etc.

CHOKED FLOW

Let us denote back pressure by $p_b$. Expansion occurs in nozzle from pressure $p_1$ to $p_b$. 
Initially when back pressure \( p_b \) is equal to \( p_1 \) there shall be no flow through the nozzle but as back pressure \( p_b \) is reduced the mass flow through nozzle increases. With the reduction in back pressure a situation comes when pressure ratio equals to critical pressure ratio (back pressure attains critical pressure value) then mass flow through nozzle is found maximum. Further reduction in back pressure beyond critical pressure value does not affect the mass flow i.e. mass flow rate does not increase beyond its’ limiting value at critical pressure ratio. Thus under these situations flow is said to be choked flow or critical flow. A nozzle operating with maximum mass flow rate condition is called choked flow nozzle. At the critical pressure ratio the velocity at exit is equal to the velocity of sound. If the back pressure is reduced below critical pressure then too the mass flow remains at maximum value and exit pressure remains as critical pressure and the fluid leaving nozzle at critical pressure expands violently down to the reduced back pressure value. Graphical representation of mass flow rate with pressure ratio and variation of pressure along length of nozzle explain the above phenomenon. State a refers to the state having back pressure more than critical pressure, state c refers to the state having back pressure equal to critical pressure and state d refers to state having back pressure less than critical pressure.

1) Dry steam at 10 bar and 100 m/s enters a nozzle and leaves it with velocity of 300 m/s at 5 bar. For 16 kg/s of steam mass flow rate determine heat drop in nozzle and final state of steam leaving nozzle assuming heat loss to surroundings as 10 kJ/kg.

**Solution:**

Given, \( C_1 = 100 \text{ m/s}, \ C_2 = 300 \text{ m/s} \)

\( P_1 = 10 \text{ bar} = 1 \text{ MPa}, \ P_2 = 0.5 \text{ MPa} \)

By steady flow energy equation between sections 1 and 2.

\[
\frac{h_1}{2} + C_1^2 + q = \frac{h_2}{2} + C_2^2 + w
\]

Here there is no work so \( w = 0 \) and heat loss, \( q = -10 \text{ kJ/kg} \)

\[
q = \left( h_2 - h_4 \right) + \left( \frac{C_2^2 - C_1^2}{2} \right)
\]

From steam table, \( h_1 = h_g \) at 1 MPa = 2778.1 kJ/kg
\[
(h_2 - h_1) = q + \left(\frac{c_i^2 - c_e^2}{2}\right)
\]
\[
(h_2 - h_1) = -10^4 + \left(\frac{100^2 - 300^2}{2}\right)
\]
\[
h_2 - h_1 = -30,000
\]

Heat drop in nozzle = 30 kJ/kg,
\[h_2 = 2748.1 \text{ kJ/kg}\]

At 5 bar, pressure,
\[h_f = 640.23 \text{ kJ/kg}, h_{fg} = 2108.5 \text{ kJ/kg}\]

Let dryness fraction at exit be \(x_2\),
\[2748.1 = 640.23 + x_2 \times 2108.5\]
\[x_2 = 0.99\]

Dryness fraction at exit = 0.99

2) Determine the mass flow rate of steam through a nozzle having isentropic flow through it. Steam enters nozzle at 10 bar, 500°C and leaves at 6 bar. Cross-section area at exit of nozzle is 20 cm\(^2\). Velocity of steam entering nozzle may be considered negligible. Show the process on h-s diagram also.

Solution:

At inlet section (1),
\[h_1 = 3478.5 \text{ kJ/kg}, s_1 = 7.7622 \text{ kJ/kg} . \text{ K}\]

Due to isentropic expansion, \(s_1 = s_2\)

At exit section (2), \(s_2 = 7.7622 \text{ kJ/kg} . \text{ K}\)

Enthalpy at rate (2) can be directly looked from mollier diagram by drawing vertical line from state
(1) till it intersects 6 bar line. Else from steam table it can be obtained as under, looking at steam table for 6 bar it indicates that the state (2) shall be superheated state because \( s_2 > s_g \) at 6 bar.

Degree of superheat can be determined by interpolation.

Entropy 7.7622 kJ/kg\(°\)K, \( S_2 \) lies between temperature of 400°C \( (S_{400°C, 6\text{ bar}} = 7.7079 \text{ kJ/kg}\(°\)K) and 500°C \( (S_{500°C, 6\text{ bar}} = 8.0021 \text{ kJ/kg}\(°\)K).

\[
7.7622 = 7.7079 + \frac{(8.0021 - 7.7079)}{(500 - 400)} \times (T_2 - 400)
\]

\[ T_2 = 418.45°C \]

Hence enthalpy at (2), \( h_2 = h_{418.45°C, 6\text{ bar}} \)

\[
h_2 = h_{400°C, 6\text{ bar}} + \frac{(h_{500°C, 6\text{ bar}} - h_{400°C, 6\text{ bar}})}{(500 - 400)} \times (418.45 - 400)
\]

\[ h_2 = 3309.51 \text{ kJ/kg}\]

Neglecting inlet velocity, \( C_1 \approx 0 \), assuming no heat loss,

\[
C_2 = \sqrt{2(h_2 - V_t^2)}
\]

\[ C_2 = 500.36 \text{ m/s} \]

Mass flow rate, \( = \frac{A_2 \times C_2}{v_2} \)

Specific volume at exit (2)

\[
v_2 = v_{400°C, 6\text{ bar}} + \frac{(v_{500°C, 6\text{ bar}} - v_{400°C, 6\text{ bar}})}{(500 - 400)} \times (418.45 - 400)
\]

\[ v_2 = 0.5281 \text{ kJ/kgK} \]

Mass flow rate, \( = \frac{20 \times 10^{-4} \times 581.36}{0.5281} \)

Mass flow rate = 2.202 kg/s

3) In a nozzle steam expands from 12 bar and 300°C to 6 bar with flow rate of 5 kg/s. Determine throat and exit area if exit velocity is 500 m/s and velocity at inlet to nozzle is
negligible. Also find coefficient of velocity at exit. Coefficient of velocity is the ratio of actual velocity of fluid at nozzle exit to the velocity at exit considering isentropic flow through nozzle.

Here velocity at exit is 500 m/s which is more than sonic velocity thus nozzle shall be converging-diverging nozzle as shown.

At inlet to nozzle, \( h_1 = 3045.8 \text{ kJ/kg} \), \( s_2 = 7.0317 \text{ kJ/kg}°\text{K} \)

Due to isentropic flow through nozzle, \( s_1 = s_2 = s_3 = 7.0317 \text{ kJ/kg}°\text{K} \) Pressure at throat section

i.e. (2) can be estimated using critical pressure ratio, which is given as

\[
\left( \frac{P_2}{P_1} \right) = \left( \frac{2}{n + 1} \right)^{\frac{n}{n-1}}
\]

For superheated steam, \( n = 1.3 \)

\[
\left( \frac{P_2}{P_1} \right) = \left( \frac{2}{1.3 + 1} \right)^{\frac{1.3}{1.3-1}}
\]

Throat pressure, \( P_2 = 6.54 \text{ bar} \)

From steam table:

At 6.54 bar, \( h_2 = 2900.05 \text{ kJ/kg} \)

\( T_2 = 224.48°C \), \( v_2 = 0.3466 \text{ m}^3/\text{kg} \), Velocity at throat

\[
C_2 = \sqrt{2(h_1 - h_2)}
\]

\[
C_2 = \sqrt{2(3045.8 - 2900.05)}
\]

\( C_2 = 539.9 \text{ m/s} \)

From continuity equation, \( m_1 = m_2 = 5 \text{ kg/s} \)

Mass flow rate, \( \dot{m} = \frac{A_2 \times C_2}{v_2} \)

\[
\dot{m} = \frac{A_2 \times 539.9}{0.3466}
\]

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Cross-sectional area at throat = 3.209\times10^{-3} \text{ m}^2

Velocity at exit of nozzle, \( C_3 = \sqrt{2(h_1 - h_3)} \)

From steam tables, Temperature at exit of nozzle, \( T_3 = 215.15 \degree \text{C} \)

Enthalpy at exit of nozzle, \( h_3 = 2882.55 \text{ kJ/kg} \)

Specific volume at exit of nozzle, \( v_3 = 0.3647 \text{ m}^3/\text{kg} \)

Ideal velocity at exit, \( C_3 = \sqrt{2 \times 10^3 (3045.8 - 2882.55)} \)

\( C_3 = 571.40 \text{ m/s} \)

Actual velocity at exit, \( C_3, \text{ actual} = 500 \text{ m/s} \)

Area at exit, \( m_1 = m_2 = m_3 = 5 \text{ kg/s} \)

\[ m_3 = \frac{A_3 \times C_{\text{actual}}}{v_3} \]

Cross-sectional area at exit = 3.647\times10^{-3} \text{ m}^2

Coefficient of velocity = \( \frac{C_{\text{actual}}}{C_3} \), Coefficient of velocity = 0.875.
QUADRANT-3

Wikis:
http://chemwiki.ucdavis.edu/Physical_Chemistry/Chemical_Equilibrium/Reversible_vs._Irreversible_Reactions

http://www.slideshare.net/qiebti/ppt-application-of-second-law-thermodynamic

http://in.ask.com/youtube?qsrc=1&o=21395&l=sem&q=videos+related+to+steam+nozzle

http://in.ask.com/youtube?q=you+tube+animation+related+to+compressible+flows&v=GqQHXtrKufQ&qs=472

Open Contents:

Applied Thermodynamics by R. K. Rajput

Applied Thermodynamics for Engineering Technologists by Eastop

Applied Thermodynamics by B. K. Venkanna, B. V. S

Basic and Applied Thermodynamics by Nag

Applied Thermodynamics by D. S. Kumar

A textbook of applied thermodynamics, steam and thermal ... by S. K. Kulshrestha

Applied thermodynamics by Anthony Edward John Hayes
QUADRANT-4

**Problems**

1) Dry steam at 10 bar and 100 m/s enters a nozzle and leaves it with velocity of 300 m/s at 5 bar. For 16 kg/s of steam mass flow rate determine heat drop in nozzle and final state of steam leaving nozzle assuming heat loss to surroundings as 10 kJ/kg.

**Solution:**

Given, $C_1 = 100$ m/s, $C_2 = 300$ m/s

$P_1 = 10$ bar = 1 MPa, $P_2 = 0.5$ MPa

By steady flow energy equation between sections 1 and 2.

$$h_1 + \frac{C_1^2}{2} + q = h_2 + \frac{C_2^2}{2} + w$$

Here there is no work so $w = 0$ and heat loss, $q = -10$ kJ/kg

From steam table, $h_1 = h_g$ at 1 MPa = 2778.1 kJ/kg

Let dryness fraction at exit be $x_2$,

$$2748.1 = 640.23 + x_2 \times 2108.5$$

$x_2 = 0.99$

Dryness fraction at exit = 0.99
2) Determine the mass flow rate of steam through a nozzle having isentropic flow through it. Steam enters nozzle at 10 bar, 500°C and leaves at 6 bar. Cross-section area at exit of nozzle is 20 cm². Velocity of steam entering nozzle may be considered negligible. Show the process on h-s diagram also.

**Solution:**

At inlet section (1),

\[ h_1 = 3478.5 \text{ kJ/kg}, \]
\[ s_1 = 7.7622 \text{ kJ/kg °K} \]

Due to isentropic expansion, \( s_1 = s_2 \)

At exit section (2), \( s_2 = 7.7622 \text{ kJ/kg °K} \)

Enthalpy at rate (2) can be directly looked from Mollier diagram by drawing vertical line from state (1) till it intersects 6 bar line. Else from steam table it can be obtained as under, looking at steam table for 6 bar it indicates that the state (2) shall be superheated state because \( s_2 > s_g \) at 6 bar.

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Entropy 7.7622 kJ/kg °K, \( S_2 \) lies between temperature of 400°C (\( S_{400°C, 6 \text{ bar}} = 7.7079 \text{ kJ/kg °K} \)) and 500°C (\( S_{500°C, 6 \text{ bar}} = 8.0021 \text{ kJ/kg °K} \)).

\[
7.7622 = 7.7079 + \frac{(8.0021 - 7.7079)}{(500 - 400)} \times (T_2 - 400)
\]

\[ T_2 = 418.45°C \]

Hence enthalpy at (2), \( h_2 = h_{418.45°C, 6 \text{ bar}} \)

\[
h_2 = h_{400°C, 6 \text{ bar}} + \frac{(h_{500°C, 6 \text{ bar}} - h_{400°C, 6 \text{ bar}})}{(500 - 400)} \times (418.45 - 400)
\]
\[ h_2 = 3270.3 + \frac{(3482.8 - 3270.3)}{100} \times 18.45 \]

\[ h_2 = 3309.51 \text{ kJ/kg}^\circ \text{K} \]

Neglecting inlet velocity, \( C_1 \approx 0 \), assuming no heat loss,

\[ C_2 = \sqrt{2(h_1 - h_2)} \]

\[ C_2 = 581.36 \text{ m/s} \]

Mass flow rate, \( \dot{m} \approx \frac{A \times C_2}{v_2} \)

Specific volume at exit (2)

\[ v_2 = v_{400^\circ\text{C}, \text{6 bar}} + \frac{(v_{500^\circ\text{C}, \text{6 bar}} - v_{400^\circ\text{C}, \text{6 bar}})}{(500 - 400)} \times (418.45 - 400) \]

\[ v_2 = 0.5137 + \frac{(0.5920 - 0.5137)}{(500 - 400)} \times (418.45 - 400) \]

\[ v_2 = 0.5281 \text{ kJ/kg}^\circ \text{K} \]

Mass flow rate, \( \frac{20 \times 10^{-4} \times 581.36}{0.5281} \)

Mass flow rate = 2.202 kg/s

3) In a nozzle steam expands from 12 bar and 300°C to 6 bar with flow rate of 5 kg/s. Determine throat and exit area if exit velocity is 500 m/s and velocity at inlet to nozzle is negligible. Also find coefficient of velocity at exit. Coefficient of velocity is the ratio of actual velocity of fluid at nozzle exit to the velocity at exit considering isentropic flow through nozzle.

Here velocity at exit is 500 m/s which is more than sonic velocity thus nozzle shall be converging-diverging nozzle as shown.

At inlet to nozzle, \( h_1 = 3045.8 \text{ kJ/kg} \), \( s_2 = 7.0317 \text{ kJ/kg}^\circ \text{K} \)

Due to isentropic flow through nozzle, \( s_1 = s_2 = s_3 = 7.0317 \text{ kJ/kg}^\circ \text{K} \) Pressure at throat section
i.e. (2) can be estimated using critical pressure ratio, which is given as

\[
\left(\frac{P_2}{P_1}\right) = \left(\frac{2}{n + 1}\right)^{\frac{n}{n-1}}
\]

For superheated steam, \( n = 1.3 \)

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\left(\frac{P_2}{P_1}\right) = \left(\frac{2}{1.3 + 1}\right)^{\frac{1.3}{1.3-1}}
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Throat pressure, \( P_2 = 6.54 \) bar

From steam table;

At 6.54 bar, \( h_2 = 2900.05 \) kJ/kg

\( T_2 = 224.48^\circ \text{C}, v_2 = 0.3466 \) m\(^3\)/kg, Velocity at throat

\[
C_2 = \sqrt{2(h_1 - h_2)}
\]

\[
C_2 = \sqrt{2(3045.8 - 2900.05)}
\]

\( C_2 = 539.9 \) m/s

From continuity equation, \( m_1 = m_2 = 5 \) kg/s

Mass flow rate, \( \dot{m} = \frac{C_2 	imes v_2}{\sqrt{2(h_1 - h_2)}} \)

\( 5 = \frac{539.9 	imes 0.3466}{\sqrt{2(3045.8 - 2900.05)}} \)

Cross-sectional area at throat = \( 3.209 \times 10^{-3} \) m\(^2\)

Velocity at exit of nozzle, \( C_3 = \sqrt{2(h_1 - h_3)} \)

From steam tables, Temperature at exit of nozzle, \( T_3 = 215.15^\circ \text{C} \)

Enthalpy at exit of nozzle, \( h_3 = 2882.55 \) kJ/kg

Specific volume at exit of nozzle, \( v_3 = 0.3647 \) m\(^3\)/kg

Ideal velocity at exit, \( C_3 = \sqrt{2 \times 10^3(3045.8 - 2882.55)} \)

\( C_3 = 571.40 \) m/s

Actual velocity at exit, \( C_3, \text{ actual} = 500 \) m/s

Area at exit, \( m_1 = m_2 = m_3 = 5 \) kg/s

\[
m_3 = \frac{A_3 \times C_{actual}}{v_3}
\]

Cross-sectional area at exit = \( 3.647 \times 10^{-3} \) m\(^2\)

Coefficient of velocity = \( \frac{C_{actual}}{C_3} \), Coefficient of velocity = 0.875.
Frequently asked Questions.

1. Differentiate between compressible and incompressible flows.

2. When is the compressibility of fluid important?

3. What is the difference between isentropic and adiabatic flows?

4. What is the relation between pressure and density of a compressible fluid for (a) isothermal process (b) adiabatic process?

5. Obtain an expression in differential form for continuity equation for one-dimensional compressible flow.

6. What is sonic velocity? On what factors does it depend?

7. What is Mach number? Why is this parameter so important for the study of flow of compressible fluids?

8. A 100 mm diameter pipe reduces to 50 mm diameter through a sudden contraction. When it carries air at 20.16°C under isothermal conditions, the absolute pressures observed in the two pipes just before and after the contraction are 400 kN/m² and 320 kN/m² respectively. Determine the densities and velocities at the two sections. Take \( R = 290 \text{ J/kg K} \).

\[ \text{Ans. 4.7 kg/m}^3 ; 3.76 \text{ kg/m}^3 ; 39.7 \text{ m/s} ; 198.5 \text{ m/s} \]

9. A normal shock wave occurs in a diverging section when air is flowing at a velocity of 420 m/s, pressure 100 kN/m², and temperature 10°C. Determine: (i) The Mach number before and after the shock, (ii) The pressure rise, and (iii) The velocity and temperature after the shock.

\[ \text{Ans. (i) 1.25} ; 0.91 ; \text{(ii) 66 kN/m}^2 \text{, (iii) 292 m/s ; 54°C} \]

10. Steam at dry saturated state enters the nozzle at 10 bar and 90 m/s velocity. Steam leaves the nozzle at 6 bar, 435 m/s. Considering heat loss of 1.51 kcal/kg of steam flow determine dryness fraction at exit of nozzle and ratio of inlet to exit cross-section area.

\[ \text{Ans.} 0.92, 3.22 \]

11. Air enters into a nozzle at 4 bar and leaves at 1 bar, 350°C and 700 m/s. Determine temperature of air entering nozzle, nozzle efficiency and nozzle exit area for air flow rate of 4 kg/s. Take \( c_p = 1.003 \text{ kJ/kg} \text{K} \).

\[ \text{Ans.} 594.27^0\text{C}, 86.04\%, 10.4 \text{ cm}^2 \]
Assignment:
1. Differentiate between compressible and incompressible flows.
2. Give the examples when liquid is treated as a compressible fluid.
3. When is the compressibility of fluid important?
4. What is the difference between isentropic and adiabatic flows?
5. What is the relation between pressure and density of a compressible fluid for (a) isothermal process (b) adiabatic process?
6. Obtain an expression in differential form for continuity equation for one-dimensional compressible flow.
7. Derive an expression for Bernoulli’s equation when the process is adiabatic.
8. How are the disturbances in compressible fluid propagated?
9. What is sonic velocity? On what factors does it depend?
10. What is Mach number? Why is this parameter so important for the study of flow of compressible fluids?
11. What do you understand by nozzle? Discuss different types of nozzles.
12. Derive the expression of velocity of fluid leaving nozzle, considering flow to be frictionless and adiabatic.
13. Obtain expression for discharge through nozzle.
14. For isentropic flow through a nozzle prove that area on p-v diagram gives the heat drop during expansion. Also show processes on T-s and h-s diagram.
15. Explain the significance of choked flow.
16. A 100 mm diameter pipe reduces to 50 mm diameter through a sudden contraction. When it carries air at 20.16°C under isothermal conditions, the absolute pressures observed in the two pipes just before and after the contraction are 400 kN/m² and 320 kN/m² respectively. Determine the densities and velocities at the two sections. Take R = 290 J/kg K.
   [Ans. 4.7 kg/m³ ; 3.76 kg/m³ ; 39.7 m/s ; 198.5 m/s]
17. An aeroplane is flying at 21.5 m/s at a low altitude where the velocity of sound is 325 m/s. At a certain point just outside the boundary layer of the wings, the velocity of air relative to the plane is 305 m/s. If the flow is frictionless adiabatic determine the pressure drop on the wing surface near this position. Assume γ = 1.4, pressure of ambient air = 102 kN/m².
   [Ans. 28.46 kN/m²]
18. A jet propelled aircraft is flying at 1100 km/h. at sea level. Calculate the Mach number at a point on the aircraft where air temperature is 20°C. Take : R = 287 J/kg K and γ = 1.4.
[Ans. 0.89]

19. An aeroplane is flying at an height of 20 km where the temperature is – 40°C. The speed of the plane is corresponding to $M = 1.8$. Find the speed of the plane. Take: $R = 287 \text{ J/kg K}$, $\gamma = 1.4$.
[Ans. 1982.6 km/h]

20. Find the velocity of bullet fired in standard air if its Mach angle is 30°.
[Ans. 680.4 m/s]

21. A normal shock wave occurs in a diverging section when air is flowing at a velocity of 420 m/s, pressure 100 kN/m$^2$, and temperature 10°C. Determine: (i) The Mach number before and after the shock, (ii) The pressure rise, and (iii) The velocity and temperature after the shock.
[Ans. (i) 1.25 ; 0.91 ; (ii) 66 kN/m$^2$, (iii) 292 m/s ; 54°C]

22. In a steam nozzle the expansion pressure ratio of 7.5 is achieved with steam entering at 30°C and leaving at 2 bar. For the steam mass flow rate of 1.2 kg/s determine the throat area considering adiabatic expansion in the absence of friction loss.
[Ans.4.45 cm$^2$]

23. Steam at dry saturated state enters the nozzle at 10 bar and 90 m/s velocity. Steam leaves the nozzle at 6 bar, 435 m/s. Considering heat loss of 1.51 kcal/kg of steam flow determine dryness fraction at exit of nozzle and ratio of inlet to exit cross-section area.
[Ans.0.92, 3.22]

**Self Answered Question & Answer**

1. Steam at 10 bar and 250°C is admitted in convergent-divergent nozzle with initial velocity of 75 m/s. Determine the velocity at exit considering isentropic flow through nozzle.
[Ans.886.35 m/s]

2. Air enters into a nozzle at 4 bar and leaves at 1 bar, 350°C and 700 m/s. Determine temperature of air entering nozzle, nozzle efficiency and nozzle exit area for air flow rate of 4 kg/s. Take $c_p = 1.003 \text{ kJ/kg K}$.
[Ans.594.27°C, 86.04%, 10.4 cm$^2$]

3. A steam nozzle has steam entering at 6 bar, 30°C and expansion occurs upto steam pressure of 1.5 bar. For the mass flow rate being 5 kg/s and nozzle exit area being 6.75 cm2 determine nozzle efficiency.
[Ans.90%]
4. A convergent-divergent nozzle has steam entering at 10 bar, 270°C and leaving at 1.2 bar. Loss in nozzle occurs only in diverging portion because of friction and amounts to 15% of total enthalpy drop. For the cone angle being 5° in diverging portion, throat diameter being 6 mm determine the length of diverging portion of nozzle.

[Ans.32 mm]

5. Steam at 1.5 bar, dry saturated is used in steam injector for feeding water into a boiler. Water enters into boiler at pressure being 20% more than boiler pressure of 20 bar. Water is taken from feed water tank at 200°C and rate of water supply is 1.67 kg/s. Determine
(a) the mass of water injected per kg of steam if coefficient of steam nozzle is 0.95. 
(b) ratio of diameters of steam nozzle to water discharge nozzle. 
(c) temperature of water entering the boiler.
Also state the assumptions made for analysis, if any.

[Ans. 5.2 kg/kg of steam, 7.3, 121°C]

6. A normal shock wave occurs in air flowing at a Mach number of 1.5. The static pressure and temperature of the air upstream of the shock wave are 100 kN/m² and 300 K. Determine the Mach number, pressure and temperature downstream of the shockwave. Also estimate the shock strength.

[Ans. 0.7 ; 246 kN/m² ; 396.17 K ; 1.46]

7. Air, thermodynamic state of which is given by pressure \( p = 230 \text{ kN/m}^2 \) and temperature \( T = 300 \text{ K} \) is moving at a velocity \( V = 250 \text{ m/s} \). Calculate the stagnation pressure if (i) compressibility is neglected and (ii) compressibility is accounted for. Take \( \gamma = 1.4 \) and \( R = 287 \text{ J/kg K} \).

[Ans. 313 kN/m², 325 kN/m²]

8. A 100 mm diameter pipe reduces to 50 mm diameter through a sudden contraction. When it carries air at 20.16°C under isothermal conditions, the absolute pressures observed in the two pipes just before and after the contraction are 400 kN/m² and 320 kN/m² respectively. Determine the densities and velocities at the two sections. Take \( R = 290 \text{ J/kg K} \).

[Ans. 4.7 kg/m³, 3.76 kg/m³, 39.7 m/s, 198.5 m/s]

9. A gas with a velocity of 300 m/s is flowing through a horizontal pipe at a section where pressure is 60 kN/m² (abs.) and temperature 40°C. The pipe changes in diameter and at this section the pressure is 90 kN/m². If the flow of gas is adiabatic find the velocity of gas at this section. Take : \( R = 287 \text{ J/kg K} \) and \( \gamma = 1.4 \).

[Ans. 113 m/s]
Test Your Skills

Choose the correct answers:

1. All real fluids are
   (a) Incompressible (b) compressible to some extent (c) compressible to any extent
   (d) none of the above.

2. A change in the state of a system at constant volume is called
   (a) isobaric process (b) isochoric process (c) isothermal process (d) adiabatic process.

3. A process during which no heat is transferred to or from the gas is called an
   (a) isochoric process (b) isobaric process (c) adiabatic process (d) isothermal process.

4. An adiabatic process is one which follows the relation
   (a) $p\rho = \text{constant}$ (b) $p\rho^\gamma = \text{constant}$ (c) $p\rho^n = \text{constant}$ ($n \neq \gamma$) (d) $v = \text{constant}$.

5. An isentropic flow is one which is
   (a) isothermal (b) adiabatic (c) adiabatic and irreversible (d) adiabatic and reversible.

6. Indica upto what Mach number can a fluid flow be considered incompressible?
   (a) 0.1  (b) 0.3  (c) 0.8  (d) 1.0.

7. Which of the following is the basic equation of compressible fluid flow?
   (a) Continuity equation (b) Momentum equation (c) Energy equation (d) Equation of state
   (e) All of the above.

8. The velocity of disturbance in case of fluids is ...... the velocity of the disturbance in solids.
   (a) less than (b) equal to (c) more than (d) none of the above.

9. Sonic velocity ($C$) for adiabatic process is given as
   (a) $C = \gamma RT$ (b) $C = \gamma RT$ (c) $C = \gamma 2RT$ (d) $C = \gamma RT$.
   where $\gamma$ = ratio of specific heats, $R$ = gas constant, $T$ = temperature.
10. The flow is said to be subsonic when Mach number is 
   (a) equal to unity (b) less than unity (c) greater than unity (d) none of the above.

11. The region outside the Mach cone is called
   (a) zone of action (b) zone of silence (c) control volume (d) none of the above.

12. A stagnation point is the point on the immersed body where the magnitude of velocity is
   (a) small (b) large (c) zero (d) none of the above.

13. A convergent-divergent nozzle is used when the discharge pressure is
   (a) less than the critical pressure (b) equal to the critical pressure
   (c) more than the critical pressure (d) none of the above.

14. At critical pressure ratio, the velocity at the throat of a nozzle is
   (a) equal to the sonic speed (b) less than the sonic speed (c) more than the sonic speed
   (d) none of the above.

15. Laval nozzle is a
   (a) convergent nozzle (b) divergent nozzle (c) convergent-divergent nozzle (d) any of the
   above.

16. A shock wave is produced when
   (a) a subsonic flow changes to sonic flow (b) a sonic flow changes to supersonic flow
   (c) a supersonic flow changes to subsonic flow (d) none of the above.

17. The sonic velocity in a fluid medium is directly proportional to
   (a) Mach number (b) pressure (c) square root of temperature (d) none of the above.

18. The stagnation pressure ($p_s$) and temperature ($T_s$) are
   (a) less than their ambient counterparts (b) more than their ambient counterparts
   (c) The same as in ambient flow (d) none of the above.

19. Across a normal shock
   (a) The entropy remains constant (b) the pressure and temperature rise
(c) The velocity and pressure decrease (d) the density and temperature decrease.

20. A normal shock wave
(a) is reversible (b) is irreversible (c) is isentropic
(d) occurs when approaching flow is supersonic.

21. The sonic speed in an ideal gas varies
(a) Inversely as bulk modulus (b) directly as the absolute pressure
(c) Inversely as the absolute temperature (d) none of the above.

22. In a supersonic flow, a diffuser is a conduit having
(a) Gradually decreasing area (b) converging-diverging passage
(c) Constant area throughout its length (d) none of the above.

23. Choking of a nozzle fitted to a pressure tank containing gas implies
(a) Sonic velocity at the throat (b) increase of the mass flow rate
(c) Obstruction of flow (d) all of the above.

24. A shock wave which occurs in a supersonic flow represents a region in which
(a) a zone of silence exists (b) there is no change in pressure, temperature and density
(c) There is sudden change in pressure, temperature and density
(d) Velocity is zero.

25. Which of the following statements regarding a normal shock is correct?
(a) It occurs when an abrupt change takes place from supersonic into subsonic flow condition
(b) It causes a disruption and reversal of flow pattern
(c) It may occur in sonic or supersonic flow
(d) None of the above.

26. For compressible fluid flow the area-velocity relationship is
(a) \(dA = dV(1 - M^2)\) (b) \(dA = dV(C^2 - 1)\) (c) \(dA = dV(M^2 - 1)\) (d) \(dA = dV(1 - V^2)\).

27. The sonic velocity is largest in which of the following?
(a) Water (b) Steel (c) Kerosene (d) Air.
28. Which of the following expressions does not represent the speed of sound in a medium?
(a) $K \rho$  (b) $\gamma RT$  (c) $K p$  (d) $dp \rho$.  

29. The differential equation for energy in isentropic flow is of the form
(a) $dVV + dp + dA = 0$  (b) $VdV + dp = 0$  (c) $2VdV + dp = 0$  (d) $dp + d(\rho V^2) = 0$.

30. Which of the following statements is incorrect?
(a) A shock wave occurs in divergent section of a nozzle when the compressible flow changes abruptly from supersonic to subsonic state  
(b) A plane moving at supersonic state is not heard by the stationary observer on the ground until it passes him because zone of disturbance in Mach cone trails behind the plane  
(c) A divergent section is added to a convergent nozzle to obtain supersonic velocity at the throat  
(d) None of the above.

ANSWERS
1. (b)  2. (b)  3. (c)  4. (b)  5. (d)  6. (b)  7. (e)  
8. (a)  9. (b)  10. (b)  11. (b)  12. (c)  13. (a)  14. (a)  
15. (c)  16. (c)  17. (c)  18. (b)  19. (b)  20. (d)  21. (d)  
22. (a)  23. (d)  24. (c)  25. (a)  26. (c)  27. (b)  28. (c)  
29. (b)  30. (c).