

## **Engineering Software**

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*Engineering Software* is pleased to announce the introduction of *Free Coursework Material*.

*Engineering Software Coursework Material* covers the following area:

 *Compressible Flow*  
*Nozzle*  
*Diffuser*  
*Thrust*

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## *Nozzle*

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### *Introduction*

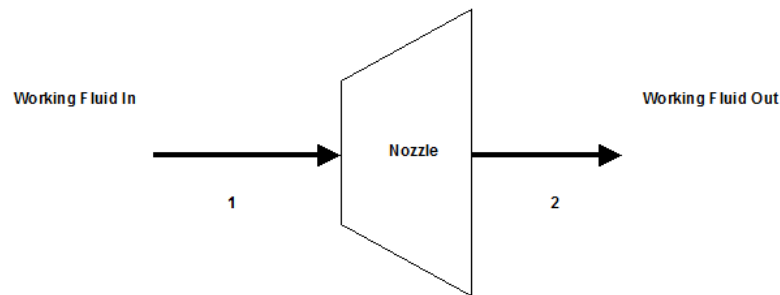
This section provides an isentropic nozzle analysis when the working fluid is air.

### *Analysis*

In the presented nozzle analysis, only air is considered as the working fluid behaving as a perfect gas -- specific heat has a constant value. Ideal gas state equation is valid --  $p v = R T$ .

Air enters a nozzle at point 1 and it exits the nozzle at point 2. Isentropic expansion is considered with no entropy change.

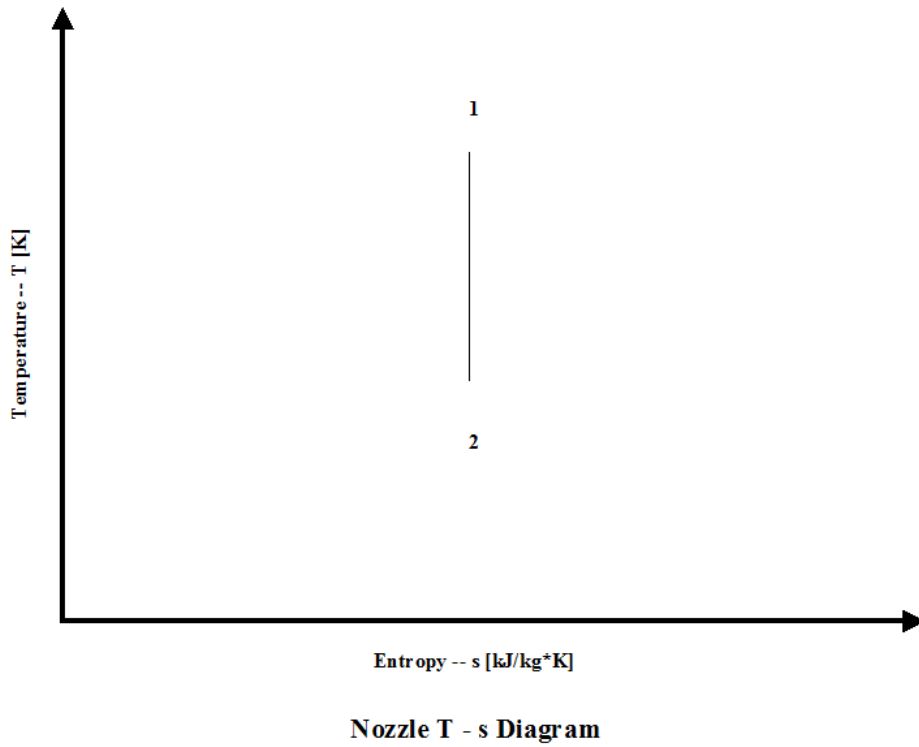
Figure 1 presents a nozzle schematic layout.



**Nozzle Schematic Layout**

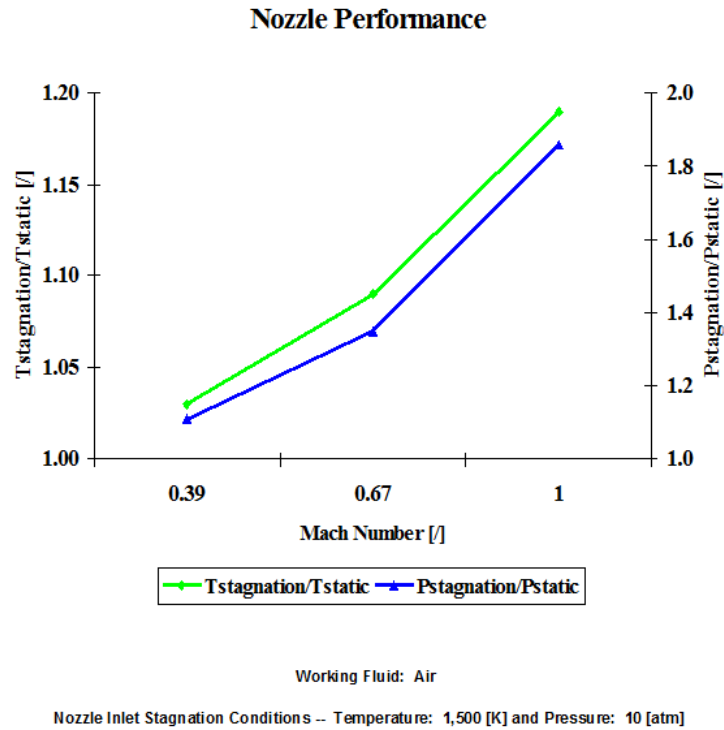
**Figure 1 - Nozzle Schematic Layout**

Figure 2 presents a nozzle temperature vs entropy diagram.



**Figure 2 - Nozzle Temperature vs Entropy Diagram**

Figure 3 presents nozzle performance -- stagnation over static temperature and pressure values -- as a function of the Mach Number. Only subsonic nozzle operation is considered. It should be noted that air enters the nozzle at the stagnation conditions of 1,500 [K] and 10 [atm] of absolute pressure.



**Figure 3 - Nozzle Performance**

One can notice that nozzle stagnation over static temperature and pressure ratio values increase with an increase of the Mach Number.

### *Assumptions*

Working fluid is air. There is no friction and heat transfer. Expansion is isentropic -- there is no entropy change. Ideal gas state equation is valid --  $p_v = RT$ . Air behaves as a perfect gas -- specific heat has a constant value.

### *Governing Equations*

$$T_t/T = (1 + M^2(\gamma - 1)/2)$$

$$p_t/p = (1 + M^2(\gamma - 1)/2)^{\gamma/(\gamma-1)}$$

$$T_t/T = (p_t/p)^{(\gamma-1)/\gamma}$$

$$v = (2c_p(T_t - T))^{1/2}$$

$$v_s = (\kappa RT)^{1/2}$$

$$M = v/v_s$$

$$\kappa = c_p/c_v$$

$$pv = RT$$

### ***Input Data***

$$T_1 = 1,500 \text{ [K]}$$

$$p_1 = 10 \text{ [atm]}$$

$$c_p = 1.004 \text{ [kJ/kg*K]}$$

$$\kappa = c_p/c_v - \text{for air } \kappa = 1.4 \text{ [/]}$$

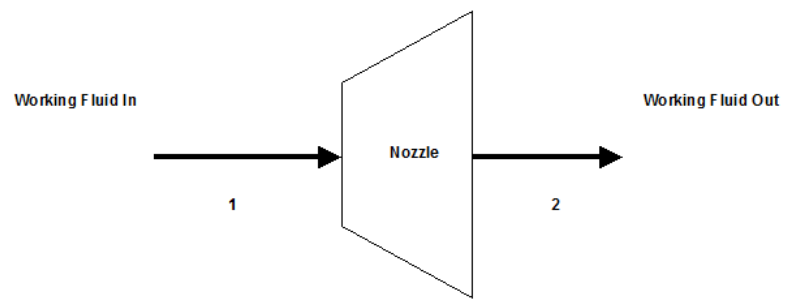
$$M = 0.39, 0.67 \text{ and } 1 \text{ [/]}$$

### ***Results***

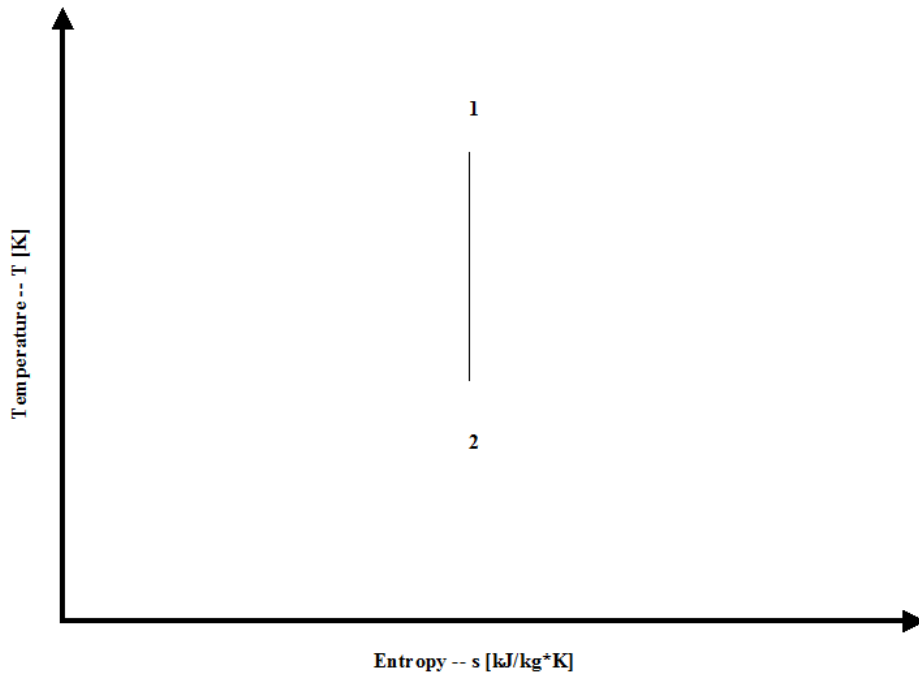
#### **Nozzle Performance vs Mach Number**

<b>Mach Number</b> [/]	<b>Temperature Ratio</b> [/]	<b>Pressure Ratio</b> [/]
0.39	1.03	1.11
0.67	1.09	1.35
1.00	1.19	1.86

*Figures*

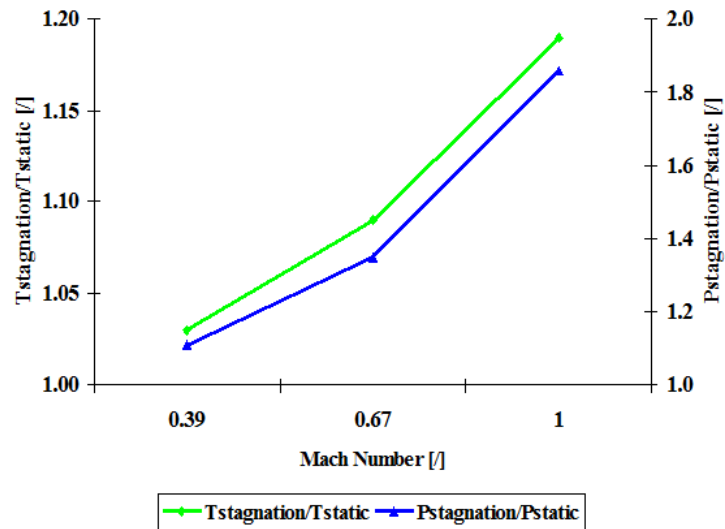


**Nozzle Schematic Layout**



Nozzle T - s Diagram

## Nozzle Performance



Working Fluid: Air

Nozzle Inlet Stagnation Conditions -- Temperature: 1,500 [K] and Pressure: 10 [atm]

### *Conclusions*

Nozzle stagnation over static temperature and pressure ratio values increase with an increase of the Mach Number.

### *References*

JANAF Thermochemical Data - Tables, 1970

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## *Diffuser*

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### *Introduction*

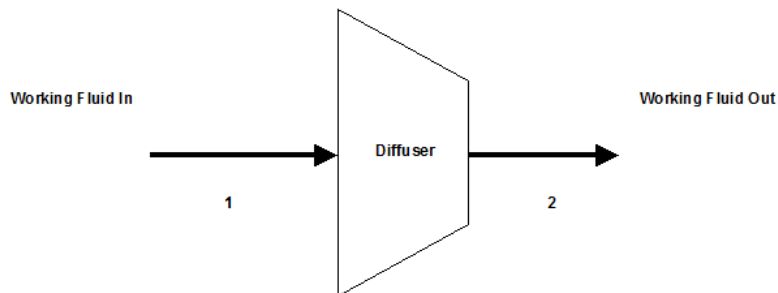
This section provides an isentropic diffuser analysis when the working fluid is air.

### *Analysis*

In the presented diffuser analysis, only air is considered as the working fluid behaving as a perfect gas -- specific heat has a constant value. Ideal gas state equation is valid --  $p v = R T$ .

Air enters a diffuser at point 1 and it exits the diffuser at point 2. Air inlet velocity gets reduced to zero resulting in the stagnation temperature and pressure increase. Isentropic process is considered with no entropy change.

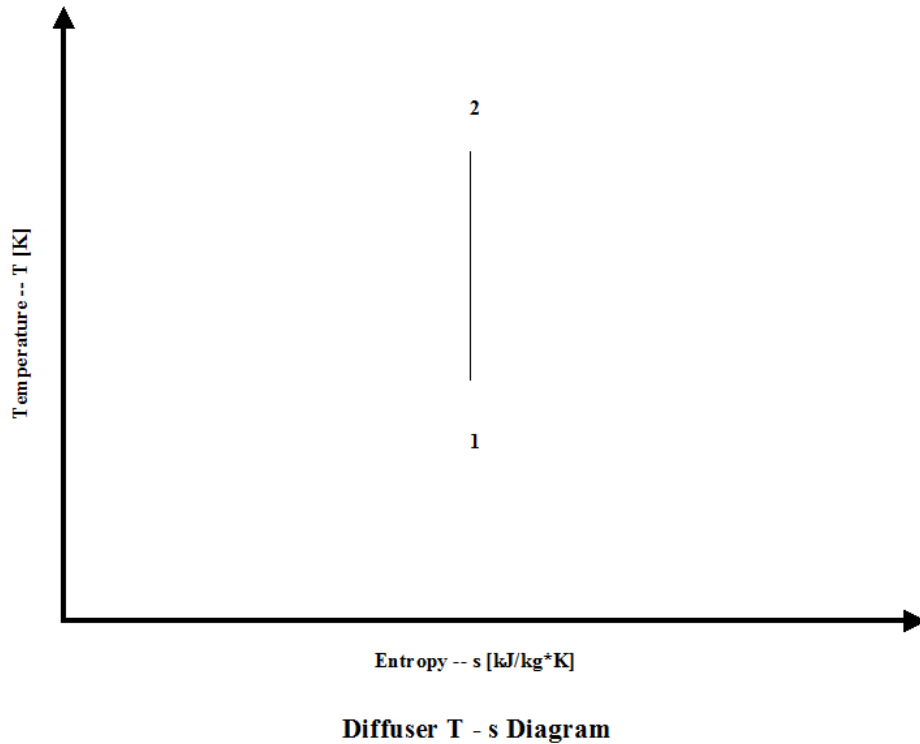
Figure 1 presents a diffuser schematic layout.



**Diffuser Schematic Layout**

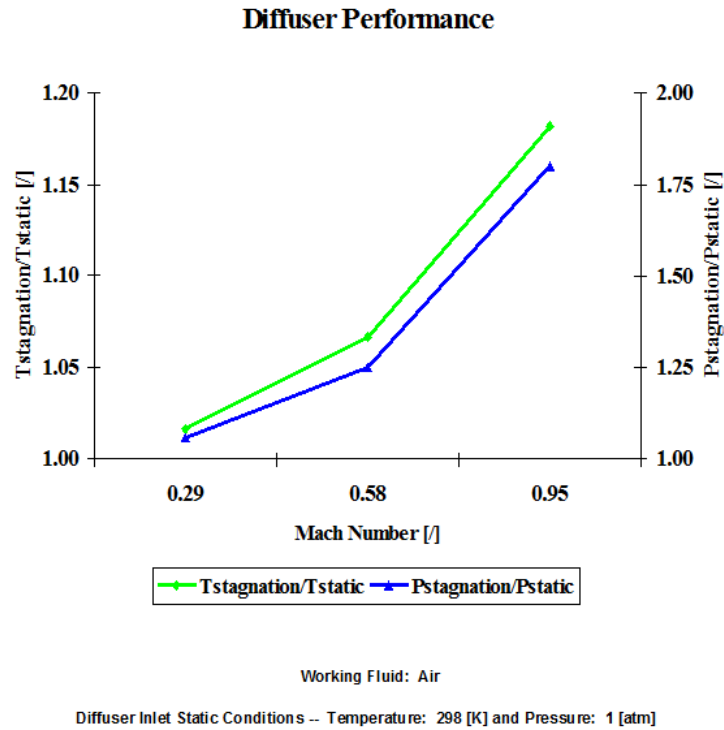
**Figure 1 - Diffuser Schematic Layout**

Figure 2 presents a diffuser temperature vs entropy diagram.



**Figure 2 - Diffuser Temperature vs Entropy Diagram**

Figure 3 presents diffuser performance -- stagnation over static temperature and pressure values - as a function of the Mach Number. Only subsonic diffuser operation is considered. It should be noted that air enters the diffuser at the static conditions of 298 [K] and 1 [atm] of absolute pressure.



**Figure 3 - Diffuser Performance**

One can notice that diffuser stagnation over static temperature and pressure ratio values increase with an increase of the Mach Number.

### *Assumptions*

Working fluid is air. There is no friction and heat transfer. Isentropic process -- there is no entropy change. Ideal gas state equation is valid --  $pv = RT$ . Air behaves as a perfect gas -- specific heat has a constant value.

### *Governing Equations*

$$T_t/T = (1 + M^2(\gamma - 1)/2)$$

$$p_t/p = (1 + M^2(\gamma - 1)/2)^{\gamma/(\gamma-1)}$$

$$T_t/T = (p_t/p)^{(\gamma-1)/\gamma}$$

$$T_t = T + v^2/(2c_p)$$

$$v_s = (\kappa RT)^{1/2}$$

$$M = v/v_s$$

$$\kappa = c_p/c_v$$

$$pv = RT$$

### ***Input Data***

$$T_1 = 298 \text{ [K]}$$

$$p_1 = 1 \text{ [atm]}$$

$$c_p = 1.004 \text{ [kJ/kg}\cdot\text{K]}$$

$$\kappa = c_p/c_v - \text{for air } \kappa = 1.4 \text{ []}$$

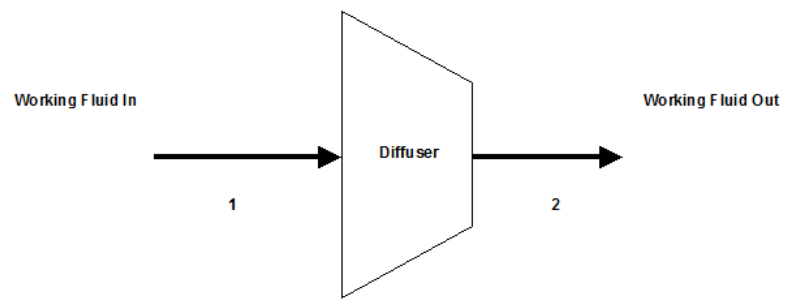
$$M = 0.29, 0.58 \text{ and } 0.95 \text{ []}$$

### ***Results***

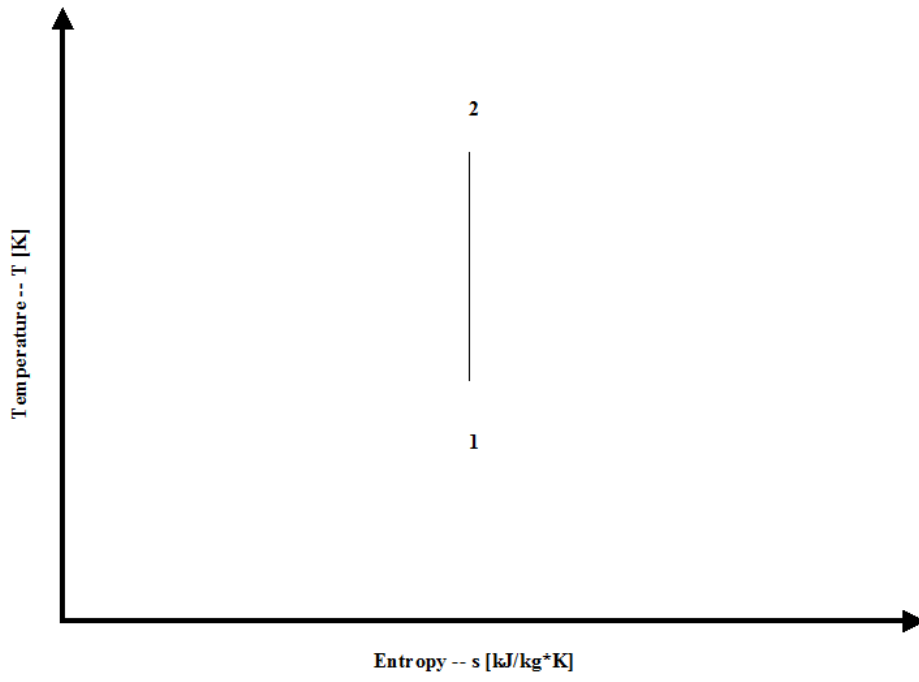
#### **Diffuser Performance vs Mach Number**

<b>Mach Number</b> [/]	<b>Temperature Ratio</b> [/]	<b>Pressure Ratio</b> [/]
0.29	1.017	1.06
0.58	1.067	1.25
0.95	1.182	1.80

***Figures***

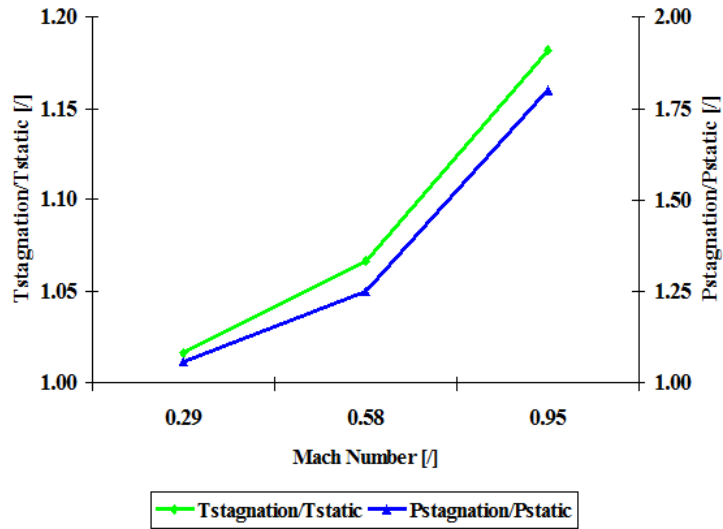


**Diffuser Schematic Layout**



**Diffuser T - s Diagram**

### Diffuser Performance



Working Fluid: Air

Diffuser Inlet Static Conditions -- Temperature: 298 [K] and Pressure: 1 [atm]

### Conclusions

Diffuser stagnation over static temperature and pressure ratio values increase with an increase of the Mach Number.

### References

JANAF Thermochemical Data - Tables, 1970

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## ***Thrust***

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### ***Introduction***

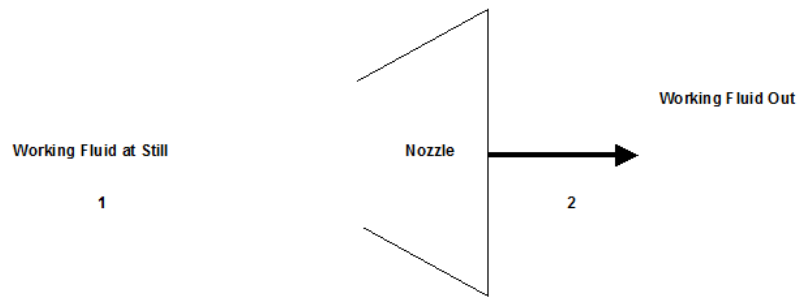
This section provides an isentropic thrust analysis when the working fluid is air.

### ***Analysis***

In the presented thrust analysis, only air is considered as the working fluid behaving as a perfect gas -- specific heat has a constant value. Ideal gas state equation is valid --  $p v = R T$ .

Air enters a nozzle at point 1 and it exits the nozzle at point 2. Isentropic expansion is considered with no entropy change.

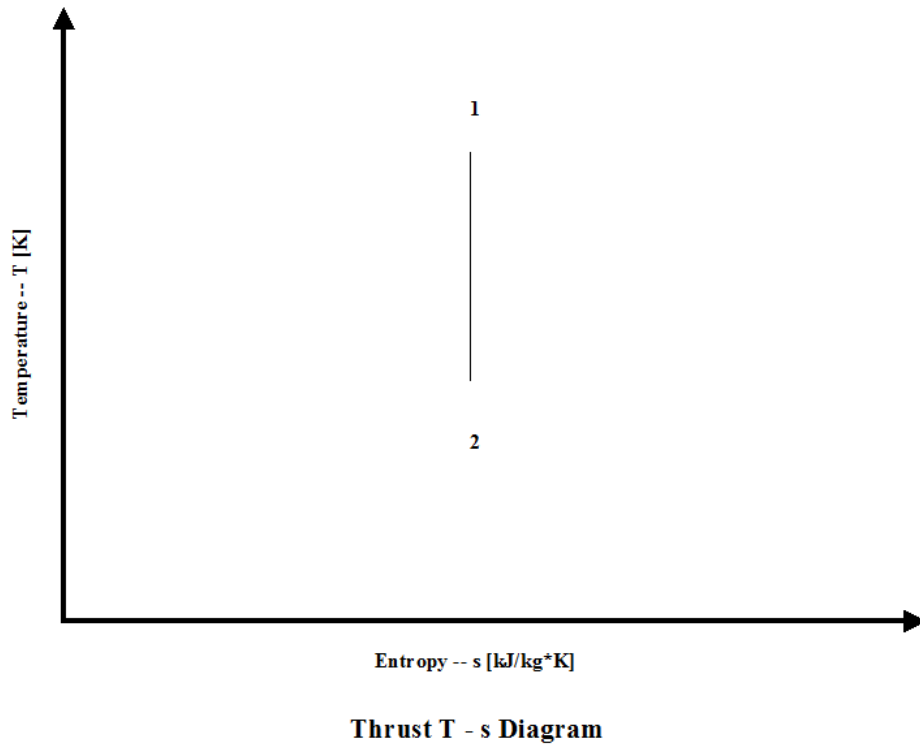
Figure 1 presents a thrust schematic layout.



**Thrust Schematic Layout**

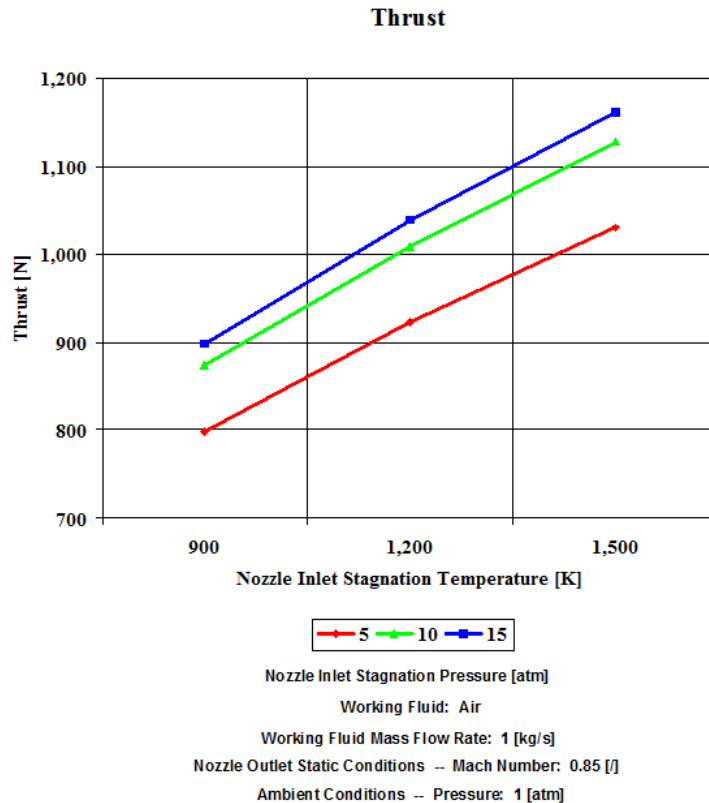
**Figure 1 - Thrust Schematic Layout**

Figure 2 presents a thrust temperature vs entropy diagram.



**Figure 2 - Thrust Temperature vs Entropy Diagram**

Figure 3 presents thrust performance as a function of the nozzle inlet stagnation temperature and pressure for a few fixed values such as: working fluid mass flow rate, nozzle outlet Mach Number and ambient pressure. Only subsonic nozzle operation is considered.



**Figure 3 - Thrust Performance**

One can notice that thrust values increase with an increase of the inlet stagnation temperature and pressure.

***Assumptions***

Working fluid is air. There is no friction and heat transfer. Expansion is isentropic -- there is no entropy change. Ideal gas state equation is valid --  $p_v = RT$ . Air behaves as a perfect gas -- specific heat has a constant value.

***Governing Equations***

$$T_t/T = (1 + M^2(\gamma - 1)/2)$$

$$p_t/p = (1 + M^2(\gamma - 1)/2)^{\gamma/(\gamma-1)}$$

$$T_t/T = (p_t/p)^{(\gamma-1)/\gamma}$$

$$v = (2c_p(T_t - T))^{1/2}$$

$$v_s = (\kappa RT)^{1/2}$$

$$M = v/v_s$$

$$\kappa = c_p/c_v$$

$$pv = RT$$

$$\text{Thrust} = vm + (p - p_a)A$$

### ***Input Data***

$$T_1 = 900, 1,200 \text{ and } 1,500 \text{ [K]}$$

$$p_1 = 5, 10 \text{ and } 15 \text{ [atm]}$$

$$c_p = 1.004 \text{ [kJ/kg}\cdot\text{K]}$$

$$\kappa = c_p/c_v - \text{for air } \kappa = 1.4 \text{ [/]}$$

$$m = 1 \text{ [kg/s]}$$

$$M = 0.85 \text{ [/]}$$

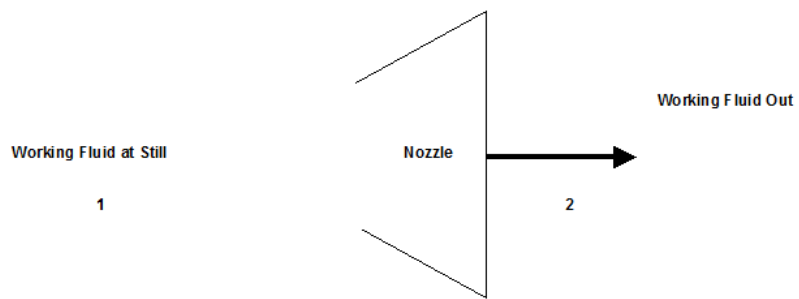
$$p_a = 1 \text{ [atm]}$$

### ***Results***

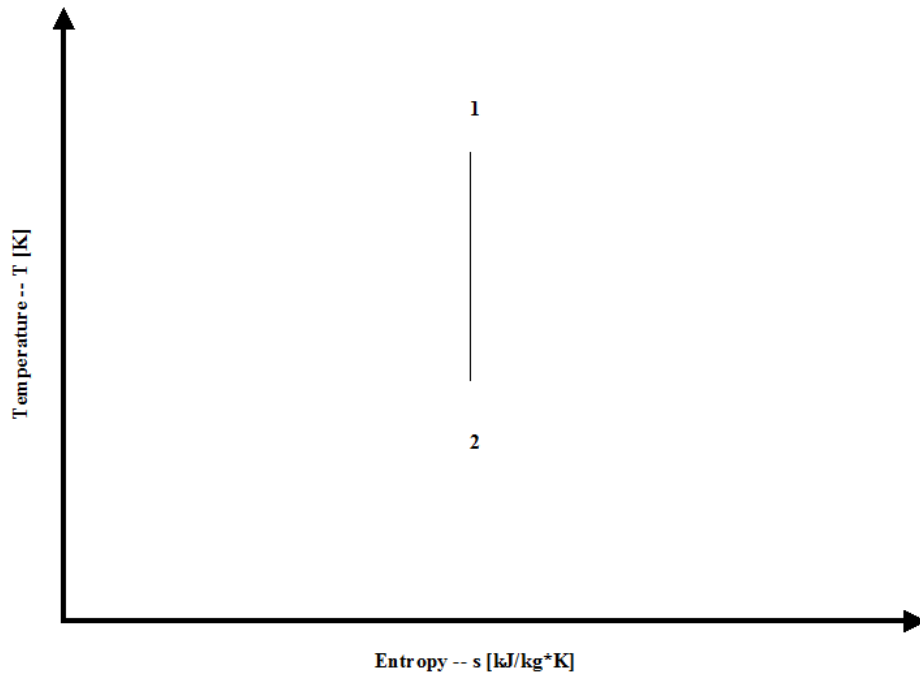
#### **Thrust Performance vs Inlet Stagnation Temperature and Pressure**

Thrust [N]	Inlet Stagnation Temperature [K]		
Inlet Stagnation Pressure [atm]	900	1,200	1,500
5	797.7	922.3	1,031.1
10	873.5	1,009.5	1,128.6
15	898.7	1,038.7	1,161.3

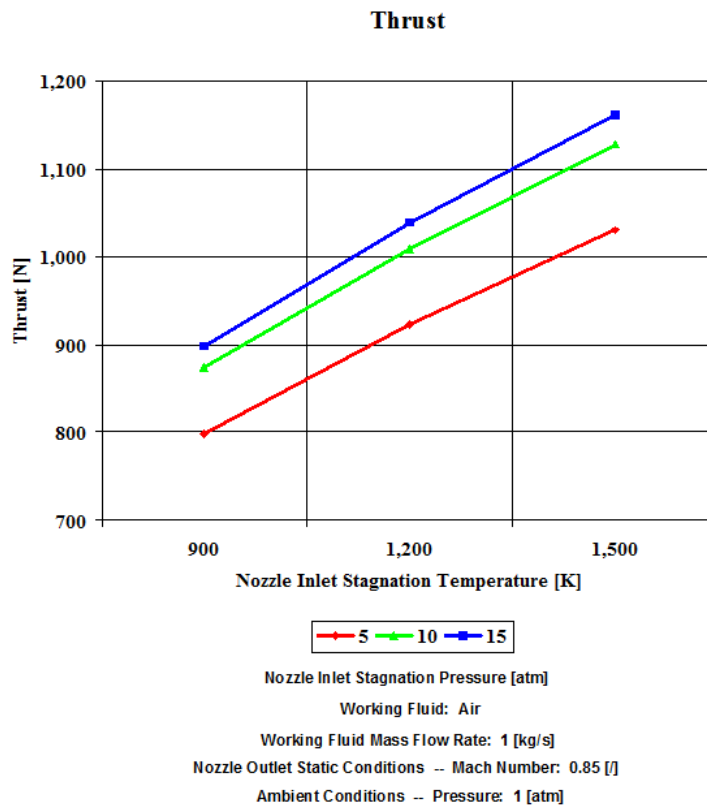
*Figures*



**Thrust Schematic Layout**



**Thrust T - s Diagram**



### *Conclusions*

Thrust values increase with an increase of the inlet stagnation temperature and pressure.

### *References*

JANAF Thermochemical Data - Tables, 1970