Lecture 21

Transport Phenomena in Furnaces: Fluid Flow

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Key Words: Fluid flow, Macroscopic Balance, Frictional Losses, Turbulent Flow

Fluid flow in furnaces

A furnace is a thermal enclosure and is employed to carry out physical and chemical processing of raw materials at high temperatures. Each of the unit processes involves either movement of gas alone or gas and liquid at high temperatures. Air is the bulkiest raw material used in several unit processes like combustion, gasification, roasting, matte and reduction smelting and oxidation etc. In combustion large quantity of air is used and large quantities of flue gases are produced. Fluid flow studies would be useful in the following:

✓ The motion of flue gases within the furnace chamber controls the rate of heat transfer and thermal gradients in the furnace

✓ Measurements of flow rates of fluid e. g. air and other liquids are required to control the process

✓ In certain physical processing like heat treatment, a gaseous atmosphere is maintained. Uniformity in the composition of the atmosphere requires to design the flow rates and rate of movement of the atmosphere.

Macroscopic Energy Balance

The engineer’s chief objective is to design and operate the equipment. Fluid movement consumes power which must be available either through a fan, blower or a compressor. Measurements and estimations of flow quantities are often necessary. Control of flow rates is important. In this connection macroscopic energy balance is very useful. In the macroscopic energy balance, the initial and final states of the thermo-physical properties of inputs and outputs are considered.
For gas flowing substantially at atmospheric pressures in furnaces, flues and ordinary metallurgical equipments, and for liquid flow system mechanical energy balance is very useful. It is

\[ \text{Mechanical energy input} + \text{other energy converted into mechanical energy} = \text{mechanical energy output} + \text{mechanical energy converted into heat} \]  

\[ (1) \]

Consider flow of fluid from point 1 to 2 at steady state as shown in the figure:

![Figure 1: System under consideration for macroscopic balance](image)

The fluid enters at the plane 1 at pressure \( P_1 \), velocity \( V_1 \) and exits at pressure \( P_2 \) and velocity \( V_2 \). Mechanical energy is added to the system by a fan as shown in the figure. The mass and energy balance at the steady state is:

\[ \text{Rate of mass in} = \text{Rate of mass out and} \]

\[ \text{Total energy input} = \text{Total energy output} \]  

\[ (2) \]

Many different kinds of energy and energy changes are to be considered when the fluid flows from plane 1 to plane 2. In the following all energy terms are expressed in \( \frac{m^2}{s^2} \) Per Kg of mass of fluid.

**Potential energy**: It is the energy possessed by the fluid by virtue of its mass, position and gravity. Potential energy is numerically equal to \( gZ_1 \) and \( gZ_2 \) at positions 1 and 2 respectively.

\[ \text{Change in potential energy} = g \Delta z \]  

\[ (3) \]

**Kinetic energy (KE)**: It is the energy of fluid by virtue of its motion and is

\[ KE = \frac{1}{2} m v^2 \]  

\[ (4) \]

In equation 4 \( V \) is the velocity of fluid. Increase in \( KE \) /unit mass as the fluid flows from position 1 to 2 is

\[ \Delta (KE) = \frac{V_2^2 - V_1^2}{2} \]  

\[ (5) \]
Pressure energy: It is the energy possessed by the fluid because it enters and exits at some pressure.

Increase in pressure energy /unit mass \( \Delta p = \left( \frac{p_2}{\rho_2} - \frac{p_1}{\rho_1} \right) \) \( \ldots \) (6)

Mechanical energy \((M)\): This energy may be added to the flow from the outside by means of a pump or fan.

Self expansion work is the mechanical work that 1 kg of fluid does on the fluid surrounding as it expands in passing through the system.

Self expansion work \( = \int P \, d \frac{1}{\rho} \)

Friction: \((F)\) It is the conversion of mechanical energy into heat due to the movement of the fluid.

Putting all energies together

\[ g(z_2 - z_1) + \frac{v_2^2 - v_1^2}{2} + \int \frac{P}{\rho} \, d \frac{1}{\rho} = \int \frac{P}{\rho} \, d \frac{1}{\rho} + F \ldots \] (7)

\[ \text{Since} \quad \frac{p_2}{\rho_2} - \frac{p_1}{\rho_1} = \int \frac{P}{\rho} \, d \frac{1}{\rho} + \int \frac{1}{\rho} \, dP \ldots \] (8)

By 7 and 8 and after rearrangement we get

\[ g(z_2 - z_1) + \frac{v_2^2 - v_1^2}{2} + \int \frac{1}{\rho} \, dP + F - M = 0 \] \( \ldots \) (9)

For incompressible fluid

\[ g(z_2 - z_1) + \frac{v_2^2 - v_1^2}{2} + \frac{p_2 - p_1}{\rho} + F - M = 0 \ldots \] (10)

This equation is also called Bernoulli’s equation. Note that this equation is in terms of unit mass of fluid flowing.

Frictional losses

Application of equation 10 requires the evaluation of frictional forces in various flow systems. Frictional losses for the flow of fluid in circular tubes can be evaluated by the Fanning equation

\[ F = 2 \, f \, \frac{L}{D} \, \bar{V}^2 \ldots \] (11)

\( f \) is friction factor, \( L \) is length and \( D \) is diameter of the pipe. Note that \( \bar{V} \) is the velocity of fluid in the pipe. It is different than velocity of fluid at plane 1. The velocity in equation 11 is equal to \( V_2 \) when the plane 2 is at just at the exit of the system. If the plane 2 is downstream the exit than \( V_2 \) is not equal to the fluid velocity in the pipe. Friction factor depends on type of flow: Laminar or turbulent flow. For the laminar flow of fluid in a pipe
\[ f = \frac{16}{Re} \text{ for } Re < 2.1 \times 10^3 \]  

(12)

Where \( Re \) is Reynold's number and is defined as

\[ Re = \frac{DV\rho}{\mu} \]  

(13)

Here \( \bar{V} \) is the velocity of fluid, \( \rho \) is density and \( \mu \) is viscosity.

In the turbulent region friction factor in a smooth pipe

\[ f = 0.0791 \times Re^{-0.25} \]  

(14)

The equation 14 is valid for \( 2.1 \times 10^3 < Re < 10^5 \). For the rough tube, friction factor is higher than calculated by equation 14. For rough tubes, \( f \) depends on surface roughness and Reynold’s number. For a given roughness, \( f \) can be determined from charts given in references at the end of this lecture.

For non-circular conduits an equivalent diameter \( De \) replaces \( D \) in the Reynold’s number

\[ De = \frac{4 \times \text{flow area}}{\text{wetted perimeter}} \]  

(15)

For a rectangular duct of cross section \( Z_1 \& Z_2 \)

\[ De = \frac{2Z_1Z_2}{(Z_1+Z_2)} \]  

(16)

**Enlargement and Contraction**

When the fluid enters from the reservoir to the nozzle, there is a sudden contraction. Similarly there is sudden expansion when the fluid exits the nozzle to the environment. Frictional losses in both sudden contraction and sudden expansion can be evaluated from

\[ F = \frac{1}{2} e f \bar{V}^2 , \]  

(17)

where \( \bar{V} \) is the fluid velocity in the smaller cross section, \( ef_1 \) is friction factor due to sudden contraction and \( (ef_2) \) is friction factor due to sudden expansion. The values of \( ef_1 \) and \( ef_2 \) depend on area ratio and Reynold’s number.

**Flow through valves and fittings**

The frictional losses associated with the fluid flowing via valves and fittings are evaluated by assigning an equivalent length to the fixture such that the \( L/D \) in eq. 11 is given by

\[ \frac{L}{D} = \left( \frac{L}{D} \right)_{\text{pipe}} + \left( \frac{L}{D} \right)_{\text{elbow}} + \left( \frac{L}{D} \right)_{\text{fixture}} \]  

(18)
The fixture could be gate valve, tee joint etc. For example a network consisting of 8 m pipe with an inside diameter 25 mm, 3 elbows (90° standard radiuses) and a gate valve 1/4 closed, and then equation 18 is

\[
\frac{L}{D} = \left( \frac{L}{D} \right)_{\text{pipe}} + 3 \left( \frac{L}{D} \right)_{\text{elbow}} + \left( \frac{L}{D} \right)_{\text{gate valve}}
\]

We substitute values of \( Le/D \)

\[
\frac{L}{D} = \frac{8}{0.025} + 3 \times 31 + 40.
\]

\[
\frac{L}{D} = 453 \text{ and this value is to be substituted in equation 11 to calculate frictional losses}
\]

References:


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