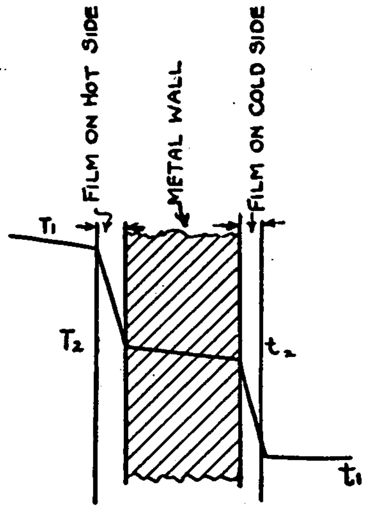
value found at the center. This condition is termed viscous or straight line flow. If the velocity be gradually increased and eddy currents set up, the average velocity becomes much greater than one-half the maximum, the friction drop increasing closely in proportion to the square of the velocity. This condition is termed turbulent flow, and the velocity at which the type of flow changes is called the critical velocity. The change is usually not well defined and often passes through an intermediate stage.



T_1 = temperature of medium being cooled or condensed.
T_2 = metal temperature in contact with the film being cooled or condensed.
t_2 = metal temperature in contact with the film being heated.
t_1 = temperature of medium being heated.

FIG. 1. TEMPERATURE GRADIENT THROUGH TWO FLUID FILMS AND METAL WALL

The critical velocity is a function of viscosity and density of the liquid and also of the pipe diameter. It is given as

$$v_c = \frac{0.122\,z}{D\,s}$$

where

v_c = critical velocity, feet per second.
z = viscosity in centipoises relative to water at 68 deg. fahr.
D = pipe diameter in inches.
s = specific gravity of liquid.

As an example, in a 2 in. pipe the critical velocities of water and a refined oil with a viscosity of 10 centipoises, or 63 seconds Saybolt Universal are, respectively, 0.059 and 0.65 ft. per second. These same liquids in a tube of ½ in. I. D. have critical velocities of 0.23 and 2.7 ft. per second.

In heat transfer equipment, the velocity should preferably be maintained above the critical value determined as above. Calculations based on data below the critical range are very unreliable, and also the heat transfer rate is low. There is always an additional turbulence set up near

the entrance and exit of a short tube, hence the heat transfer for a short tube is greater than for a long one.

Correlation of heat transfer data was delayed many years by the search for equations to fit overall coefficients. Greater progress was made by resolving the overall thermal resistance into parts and treating it in a manner analogous to an electric circuit. Temperature corresponds to voltage, heat flow to current, and thermal resistance to electrical resistance. The individual resistances of cooling film, metal, scale, and heating film added together give the total resistance, and the reciprocal of this sum gives the overall conductance or heat transmission coefficient. Fig. 1 shows the temperature relations existing during heat transfer through two fluid films and a metal wall.

U = overall heat transmission or conductance (B.t.u. per hour per square foot per deg. fahr).
H = total heat transmitted (B.t.u. per square foot per hour).
$h_c = \frac{1}{r_c}$ = conductance of cooling film (B.t.u. per hour per square foot per deg. fahr.)
$h_m = \frac{1}{r_m}$ = conductance of metal. (B.t.u. per hour per square foot per deg. fahr.)
$h_w = \frac{1}{r_w}$ = conductance warming film. (B.t.u. per hour per square foot per deg. fahr.)
$R = \frac{1}{U}$ = total resistance to flow of heat from heating medium to cooling medium.

$$r_c = \frac{T_1 - T_2}{H} \qquad r_m = \frac{T_2 - t_2}{H} \qquad r_w = \frac{t_2 - t_1}{H}$$

Adding the above equations

$$R = \frac{1}{U} = \frac{(T_1 - T_2) + (T_2 - t_2) + (t_2 - t_1)}{H} = \frac{T_1 - t_1}{H}$$

Any additional resistances, caused by scale or dirt, should be added to give the total resistance.

To obtain a value for the film resistance of a liquid flowing in a pipe, Morris and Whitman give a curve as the result of many experiments, which can be considered approximately a straight line, with the formula

$$\frac{hD}{K} = 0.83\left(\frac{DV}{z}\right)\left(\frac{cz}{K}\right)^{0.37}$$

h = heat transfer for liquid film (B.t.u. per hour per square foot per deg. fahr.)
D = inside diameter of tube in inches.
K = thermal conductivity of liquid (B.t.u. per hour per square foot per deg. fahr. per foot thickness).
V = mass velocity (pounds per second per square foot).
z = viscosity in centipoises, relative to water at 68 deg. fahr.
c = specific heat (B.t.u. per pound per deg. fahr.)

If we let Q represent the quantity flowing through the tube, $Q = 0.005454\,D^2 V$,

$$h = 1.52\,\frac{K}{D}\,\frac{Q}{D\,z}\left(\frac{cz}{K}\right)^{0.37} = 1.52\,\frac{Q}{D^2}\left(\frac{K}{z}\right)^{0.63} c^{0.37}$$

On this basis, it is seen that if other conditions remain constant, the rate of heat transfer increases directly with the quantity flowing, inversely