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Theoretical investigation of steam jet cleaning

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THEORETICAL INVESTIGATION OF

STEAM JET CLEANING

BY

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ABSTRACT

Steam cleaning methods are used by industries to remove mass of dirt and grease deposits from machine parts and other surfaces. It is necessary to know the rate at which this mass can be removed from a surface. The present investigation was made to determine this rate of mass removal. The mass transfer rate is influenced by two phenomena; namely, heat transfer and momentum transfer. Both of these were discussed and the results obtained from the analysis were used in determining the total mass transfer rate. The effects of various parameters, such as density and velocity of the cleaning fluid, jet impingement angle, etc., on the total mass transfer rate were included.

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NOMENCLATURE

$\dot{a}$	Mass rate of flow, lb_m/hr
B_h	Driving force for heat transfer theory, dimensionless
B_m	Driving force for momentum theory, dimensionless
c_f	Friction factor, dimensionless
c_p	Specific heat at constant pressure, $Btu/lb_m\text{-}^{o}F$
d	Exit diameter of nozzle, ft
D	Diffusion coefficient, ft^2/hr
g_h	Surface conductance for heat transfer theory, $lb_m/hr\text{-}ft^2$
g_m	Mass flux for momentum theory, $lb_m/hr\text{-}ft^2$
g_o	Conversion factor, 4.16×10^8 $lb_m ft/lb_f hr^2$
G	Mass velocity, $lb_m/hr\text{-}ft^2$
h	Heat transfer coefficient, $Btu/hr\text{-}ft^2\text{-}^{o}F$
i	Enthalpy, Btu/lb_m
J	Mechanical equivalent of heat, 778.17 $ft\text{-}lb_f/Btu$
k	Thermal conductivity, $Btu/hr\text{-}ft\text{-}^{o}F$
L	Distance from heat transfer surface to nozzle, ft
L_v	Latent heat of vaporization, Btu/lb_m
$\dot{m}''$	Rate of mass removal for heat transfer theory, $lb_m/hr\text{-}ft^2$

$\dot{m}_X$, $\dot{m}_Y$, $\dot{m}_Z$	Mass flow rates of fluid streams X,Y,Z, lb_m/hr
p	Pressure, lb_f/ft^2
P	Any conserved property
$\dot{q}''$	Heat flux, $Btu/hr\text{-}ft^2$
t	Temperature, ^oF
u	Tangential velocity, ft/hr
V	Velocity in the direction of flow, ft/hr
$\dot{w}''$	Rate of mass removal for momentum theory, $lb_m/hr\text{-}ft^2$
x, y, z	Space coordinates in cartesian system
$\alpha = \frac{k}{\rho c_p}$	Thermal diffusivity, ft^2/hr
β	Mass transfer coefficient, ft/hr
δ	Thickness, ft
$\theta = \frac{\phi}{90}$	Reduced nozzle angle, dimensionless
μ	Absolute viscosity, $lb_m/hr\text{-}ft$
ρ	Density, lb_m/ft^3
τ	Shear stress, lb_f/ft^2
ϕ	Jet impingement angle, degrees from horiz.
$Le = \frac{\alpha}{D}$	Lewis number, dimensionless
$Nu = \frac{hd}{k}$	Nusselt number, dimensionless
$Pr = \frac{c_p \mu}{k}$	Prandtl number, dimensionless
$Re = \frac{dV\rho}{\mu}$	Reynolds number, dimensionless

<u>Subscripts</u>

1, 2	Initial and final conditions
d	Based on exit diameter of nozzle
F	Evaluated at F-state or surface
G	Evaluated at G-state or surface
L	Evaluated at L-state or surface
S	Evaluated at S-state or surface
T	Transferred substance
TL	Evaluated at L-state or surface for the transferred substance
TS	Evaluated at S-state or surface for the transferred substance
x	Based on length of heat transfer surface
X, Y, Z	Fluid streams

INTRODUCTION

The rapid technological advances in recent years have demanded comprehensive studies of each of the many unit operations on which industrial processes depend. Of all the activities engaged in by industrial enterprises, there probably is none more universal than cleaning or deterging. All industrial operations are faced with cleaning problems.

One of the most modern ways of industrial cleaning is by use of the steam cleaning methods. Many cleaning jobs, formerly done by hand brushing, wiping, and scrapping, can be done faster, better and at less cost by using steam cleaners. Some industrial cleaning is done with just a steam hose; but more modern equipment uses water and detergent solution as cleaning media, whereas steam does the job of carrying them and providing velocity, mass, and momentum. For the latter case, the name 'steam cleaning' is a rather misleading one; however, this name is so widely accepted that it is impractical to use some other term. A modern steam cleaner is a simple mechanical device which combines the four essentials of efficient cleaning — water, detergent, heat and friction (high fluid velocity).

A modern steam cleaner is designed and equipped to remove dirt, grease, and heavy oil deposits from machine parts and other surfaces. It has a wide field of applications which includes the cleaning of automotive and

truck fleets, aircraft engines and parts, farm machinery, earth moving equipment, snow removal equipment, railroad equipment, tanks and vats, buildings, sewage plants, etc. Figure 1 shows a flow diagram illustrating the basic elements of a steam cleaner. The advantages of steam jet cleaning arise from:

(a) The softening and dispersing effect of the released heat energy.

(b) The cutting velocity and scrubbing action of the fluid jet.

(c) The chemical and physical action of the detergent compound.

In a steam cleaning process, a jet of the cleaning fluid, under pressure, is directed at a suitable angle against a dirty surface. The process involves the removal of mass from the surface by the combined phenomena of heat-, mass-, and momentum-transfer. The purpose of this research is (i) to investigate a method for predicting theoretically the total rate of mass removal from the surface, and (ii) to determine the effect of various parameters on this rate of mass removal.

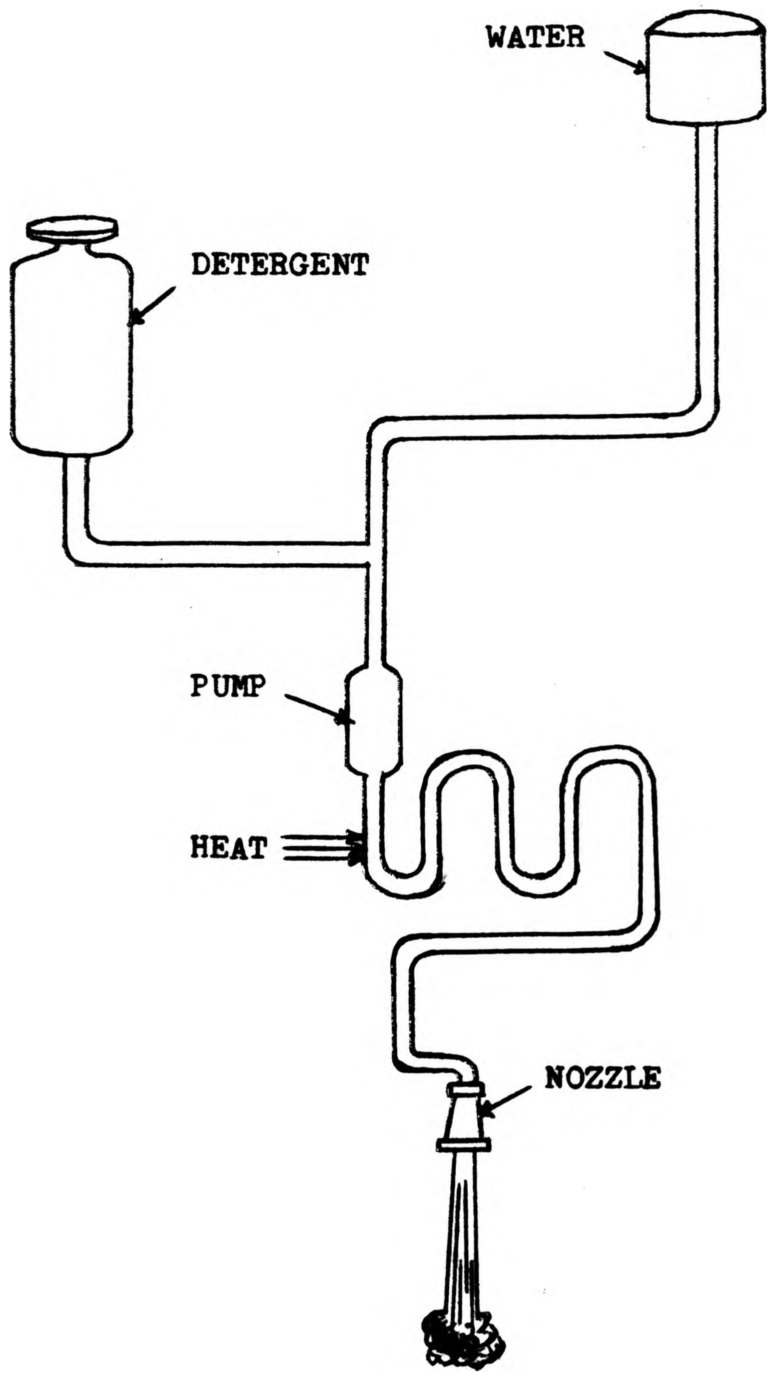

Figure 1. Simplified flow diagram for a steam cleaner.

REVIEW OF LITERATURE

In spite of the fact that the steam cleaning process has been utilized by industries for several years, no theoretical or experimental treatment exists by which the rate of mass removal from the surface can be predicted.

Spalding [1]* has shown that every mass transfer problem, including those with simultaneous heat transfer and chemical reaction, can be treated by relations of the "Ohm's Law" type: $\dot{m}'' = g.B$, where $\dot{m}''$ is the required mass transfer rate through the surface, g is a surface conductance and B is a dimensionless driving force. He has derived relations for calculating g and B for various cases. Spalding [2] has also treated the mass transfer problem by a standard formulation which is derived from the differential equations of conservation and flux.

Numerous experimental investigations have been conducted to determine the heat transfer coefficients between a flat plate and a fluid jet impinging on it. Nevins and Ball [3] investigated the heat transfer coefficient between a flat plate and a pulsating air jet impinging on it at an angle. Gardon and Cobonpue [4] studied the performance as heat transfer agents both of multiple jets issuing from arrays of nozzles and of a

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* Numbers in brackets designate references in Bibliography.

single jet. Their study was also concerned with the variation of heat transfer coefficients from point to point in the surface. Freidman and Mueller [5] reported heat transfer measurements between air and a horizontal heated plate where the air impinged vertically upon the plate from a multitude of holes, slots, or nozzles. Smirnov, Verevochkin and Brdlick [6] studied the heat transfer between a submerged jet of water and a plate held normal to the flow. Perry [7] has made measurements of the heat transfer from air jets, with temperature difference of up to 750° F. and velocities of up to 250 fps, impinging on a plane surface at various angles. Among other researchers on the problem, Vickers [8] studied local heat transfer coefficients of fluid jet impinging on a normal surface at the laminar flow region, and Huang [9] conducted experiments to study the single jet, simple multiple jet and general multiple jet systems.

Gadberry [12] has given a general view of the steam cleaning process. Some manufacturers of steam cleaning equipment have conducted tests to determine the most efficient design particulars for specific applications. Clayton Manufacturing Company [13] is one of such concerns.

ANALYTICAL TREATMENT

It can be stated that in a steam cleaning process, the mass is removed from the surface in two ways:

(a) The amount transferred or evaporated, which can be calculated from heat transfer theory; and

(b) The amount blown off, which can be calculated from momentum principles.

The total rate of mass removal is the sum of the rates of mass removal in each of the two cases. Both the heat transfer theory and momentum principle will be treated in turn to obtain relations for calculating the mass removal rate in each case.

Figure 2 shows schematically the action of a jet of cleaning fluid impinging on grease deposits on a surface.

HEAT TRANSFER THEORY

In the present problem, since the jet of cleaning fluid at high velocity impinges on the grease deposits on the surface, there is large-scale relative motion between the two phases. The transfer of mass takes place by what is known as convective mass transfer. Just as it is conventional to distinguish between conductive and convective heat transfer, so the term diffusional mass transfer is reserved for processes in which there is no

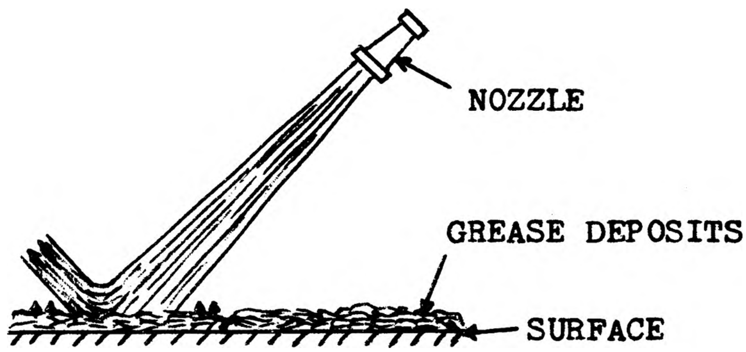

Figure 2. Illustrating the action of a jet of cleaning fluid.

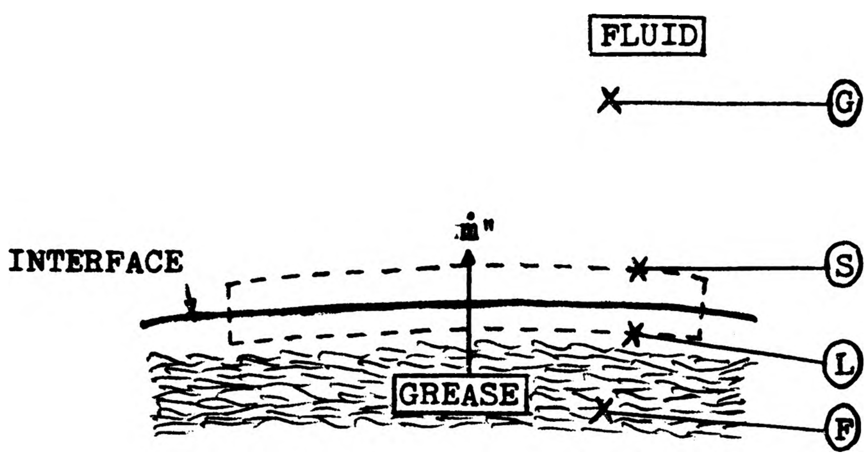

Figure 3. Illustrating an element of the interface between the cleaning fluid and grease deposits.

relative motion. Thus, convective mass transfer corresponds to convective heat transfer. The flow conditions, fluid properties, and boundary shapes have influence on the convective heat transfer as well as the convective mass transfer mechanism. Figure 3 illustrates an element of the interface separating the cleaning fluid from the grease deposits. It will be supposed that the thickness of the boundary-layer on either side of the interface is relatively thin. Hence, outside these regions it is meaningful to speak of the 'bulk' states of the fluid and of the grease deposits. These will be designated the G- and F-states respectively. The state of the fluid immediately adjacent the interface is generally different in both composition and temperature from that of the bulk of the fluid: it will here be called the S-state. Similarly, the state of the grease deposits immediately adjacent the interface will be called the L-state. In addition to the G-, F-, S-, and L-states, one further state will require consideration; this is the T-state. It is composed of the 'transferred substance' — the grease deposits in the present case. However, this state is not normally possessed by the mixture at any particular location and hence is not shown in Fig. 3.

The aim of convective mass transfer theory is to calculate the rate of transfer of material across the

boundary. This rate is related to the fluid and boundary properties by an equation of the Ohm's law form, namely:

$$\dot{m}'' = g_h \cdot B_h \qquad \ldots\ldots (1)$$

where $\dot{m}''$ is the mass transfer flux, $lb_m/hr\text{-}ft^2$

g_h is a surface conductance expressing the influence of fluid-mechanical factors: fluid velocity, surface shape, etc., $lb_m/hr\text{-}ft^2$

B_h is a dimensionless driving force, dependent for its value on the composition and temperature of the fluid stream, of the fluid in contact with the surface, and of the transferred substance.

Methods for calculating the surface conductance and the driving force will be discussed in turn.

<u>Surface Conductance</u>

The surface conductance, g_h, is to be deduced from convective heat transfer theory by means of Lewis' equation [10] :

$$\beta = \frac{h}{\rho c_p} \qquad \ldots\ldots (2)$$

where $\beta = \dfrac{g_h}{\rho}$ = Mass transfer coefficient, ft/hr

h = Surface heat transfer coefficient, $Btu/hr\text{-}ft^2\text{-}^{\circ}F$

ρ = Density of the fluid, lb_m/ft^3

c_p = Specific heat of the fluid at constant pressure, Btu/lb_m-^oF.

Lewis' equation is valid when the Lewis number, Le, is unity. The Lewis number is an important parameter when a mass transfer process is to be obtained from a corresponding heat transfer process. Since this is the case in the present problem, the use of Eq. (2) is justified. The expression for the surface conductance becomes

$$g_h = \frac{h}{c_p} \qquad \text{..... (3)}$$

Due to the complicated nature of the present problem, it is not possible to derive an analytical expression for the heat transfer coefficient, h. Hence, it is to be obtained from the results of experimental data expressed in the form of an empirical formula. A physical consideration of the problem will clearly indicate that the heat transfer coefficient should depend upon the bulk state fluid properties, the exit diameter of the nozzle, the distance of the surface from the nozzle, the angle of impingement, and the average jet velocity.

Nevins and Ball [3] derived the following empirical relation for the heat transfer coefficient between a pulsating air jet and a flat plate:

$$Nu = [7.1 - 0.095\ (L/d)]\ [\theta]^{[0.35 - 0.008\ (L/d)]} \left[\frac{Re_d}{1000}\right]^{0.63} \qquad \ldots\ldots (4)$$

where $Nu = \frac{hd}{k}$, Nusselt number, dimensionless

$Re_d = \frac{dV\rho}{\mu}$, Reynolds number, dimensionless

d = Nozzle diameter, ft

L = Distance from plate to nozzle, ft

$\theta = \phi/90$, Reduced nozzle angle, dimensionless

ϕ = Jet impingement angle, degrees from horizontal

V = Jet velocity at nozzle, ft/hr

k = Thermal conductivity of the fluid, Btu/hr-ft-^{o}F

ρ = Density of the fluid, lb_m/ft^3

μ = Absolute viscosity of the fluid, lb_m/hr-ft

The Nusselt number was found to be independent of the pulsations for the ranges of variables covered in the investigation. Hence Eq. (4) could be applied to steady flow as well. Although the equation was obtained with air as the working fluid, it can be used for any other fluid if the Prandtl number, Pr, for the fluid is approximately equal to that for air, as suggested by Vickers [8].

The results of tests conducted under similar conditions with steady fluid jet impinging on flat plate by other investigators [6, 7] are in close agreement with Eq. (4). Hence Eq. (4) shall be used in the problem of

calculating the heat transfer coefficient.

Combining Eq. (4) with Eq. (3), the value of the surface conductance, g_h, will be obtained.

Driving Force

In order to derive the general expression for the driving force, B_h, it will be necessary to define the conserved property of a mixture. A property P of a mixture is said to be a conserved property if it obeys the law,

$$\dot{m}_X P_X + \dot{m}_Y P_Y - \dot{m}_Z P_Z = 0 \qquad \text{..... (5)}$$

where X and Y are two fluid streams, which flow together adiabatically and steadily, to form a third stream Z;

$\dot{m}_X$, $\dot{m}_Y$ and $\dot{m}_Z$ are the mass flow rates, lb_m/hr, of each of these streams;

P_X, P_Y and P_Z are the values of the property P in the respective streams.

Figure 4 illustrates the control volume for the heat transfer problem. In addition to the S- and L-surfaces, the G-surface is introduced. It is supposed to be in a region where the fluid state is scarcely different from that in the bulk of the fluid. Hence, the whole region in which the fluid state differs appreciably from that in the bulk of the fluid, is to be found between the G- and S-surfaces. As shown in Fig. 4, the flux of material which

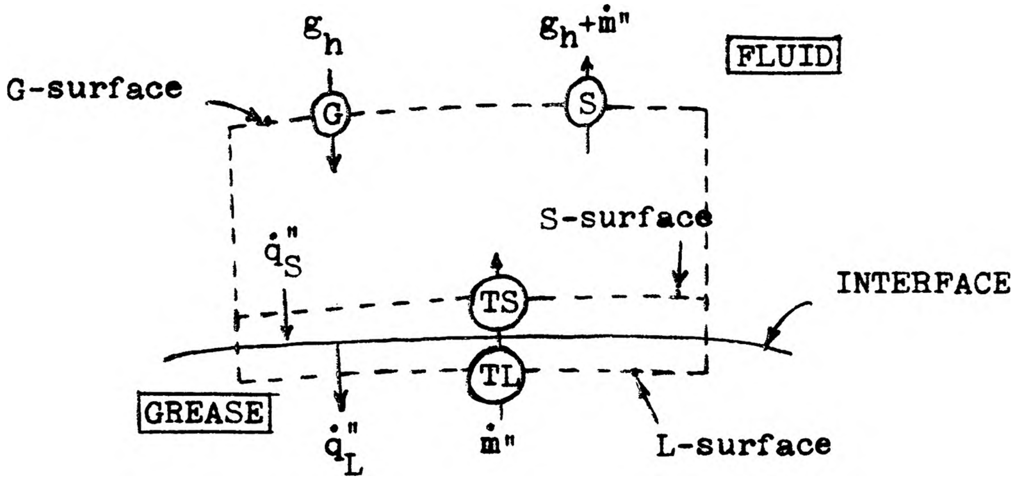

Figure 4. Control volume for heat transfer problem.

crosses the G-surface in the direction of the S-surface is the flux g_h. By applying the principle of mass conservation to the control volume comprising the G- and S-surfaces, it is seen that the magnitude of the flux through the G-surface, away from the S-surface, of fluid in the S-state is $g_h + \dot{m}''$.

Considering Fig. 4, and noting that X, Y and Z in the definition of P may be replaced by G, T and S, Eq. (5) becomes

$$g_h P_G + \dot{m}'' P_T - (g_h + \dot{m}'') P_S = 0 \qquad \ldots\ldots (6)$$

Simplifying, $\dfrac{\dot{m}''}{g_h} = \dfrac{P_G - P_S}{P_S - P_T}$

But the quantity on the left hand side of the equation is the driving force, B_h. Hence

$$B_h = \frac{P_G - P_S}{P_S - P_T} \qquad \ldots\ldots (7)$$

This is a general expression for the driving force. In order to obtain a particular expression for use in the present problem, it will be necessary to apply the steady-flow energy equation to the GS-volume.

The fundamental energy equation for steady flow of fluid between any two sections 1 and 2 can be expressed as

$$i_1 + \frac{V_1^2}{2g_o J} = i_2 + \frac{V_2^2}{2g_o J} - \text{heat supplied} \qquad \ldots\ldots (8)$$

where i_1 and i_2 are the enthalpies at sections 1 and 2, Btu/lb_m

V_1 and V_2 are the velocities in the direction of flow at sections 1 and 2, ft/hr

g_o is a constant having the value $4.16\text{x}10^8$ $lb_m ft/lb_f hr^2$

J is the mechanical equivalent of heat, 778.17 ft-lb_f/Btu.

Considering Fig. 4 and making the energy balance, the following equation is obtained:

$$g_h\left(i_G+\frac{V_G^2}{2g_oJ}\right) + \dot{m}''\left(i_{TS}+\frac{V_{TS}^2}{2g_oJ}\right) - (g_h+\dot{m}'')\left(i_S+\frac{V_S^2}{2g_oJ}\right) = -\dot{q}''_S \qquad \text{..... (9)}$$

where i_G is the enthalpy of the bulk fluid as it crosses the G-surface, Btu/lb_m

i_S is the enthalpy of the mixture as it crosses the S-surface, Btu/lb_m

i_{TS} is the enthalpy of the transferred substance—grease—as it crosses the S-surface, Btu/lb_m

V_G is the velocity of the fluid jet at the G-surface, ft/hr

V_S is the velocity of the fluid jet at the S-surface, ft/hr

V_{TS} is the velocity of the transferred substance—grease—at the S-surface, ft/hr

$\dot{q}''_S$ is the heat flux through the S-surface, Btu/hr-ft^2.
Rearrangement of Eq. (9) leads to

$$\frac{\dot{m}''}{g_h} = \frac{i_G - i_S + \dfrac{V_G^2 - V_S^2}{2g_oJ}}{i_S - i_{TS} + \dfrac{V_S^2 - V_{TS}^2}{2g_oJ} - \dfrac{\dot{q}''_S}{\dot{m}''}}$$

OR

$$B_h = \frac{i_G - i_S + \dfrac{V_G^2 - V_S^2}{2g_oJ}}{i_S - i_{TS} + \dfrac{V_S^2 - V_{TS}^2}{2g_oJ} - \dfrac{\dot{q}''_S}{\dot{m}''}} \quad \ldots\ldots (10)$$

The velocity V_{TS} is very small and hence may be neglected. Equation (10) then reduces to

$$B_h = \frac{i_G - i_S + \dfrac{V_G^2 - V_S^2}{2g_oJ}}{i_S - i_{TS} + \dfrac{V_S^2}{2g_oJ} - \dfrac{\dot{q}''_S}{\dot{m}''}} \quad \ldots\ldots (11)$$

This is the required expression for the driving force.

Finally, by substituting proper values for the conductance, g_h, and the driving force, B_h, from Eqs. (3)

and (11) into Eq. (1), the mass transfer flux $\dot{m}''$ can be easily calculated.

This method of calculating the mass transfer flux provides a powerful tool for the solution of mass transfer problems and is sufficiently accurate for most engineering applications. However, it is necessary to make a few and relatively minor assumptions in order to simplify the analysis. The assumptions made here are as follows:

(a) The lateral heat loss over the width of the heat transfer surface is considered negligible.

(b) The heat loss due to radiation from the system to the surroundings is neglected.

(c) Lewis' equation is used to determine the surface conductance, g_h.

(d) Equation (4) is used to determine the heat transfer coefficient, h, for steady fluid jet if the Prandtl number for the fluid is approximately equal to that for air.

(e) In the application of the steady flow energy equation, shear work, gravitational, electrical and magnetic effects are assumed to be absent.

MOMENTUM PRINCIPLE

As stated earlier, the high velocity of the striking jet will tend to peel off the soil by under-cutting it.

A shear stress will be exerted by the fluid on the interface as a result of frictional processes in the boundary layer.

As in the case of the heat transfer theory, the rate of mass removal here is given by an equation of the Ohm's law form, namely:

$$\dot{w}'' = g_m \cdot B_m \qquad \text{..... (12)}$$

where $\dot{w}''$ is the rate of mass removal, $lb_m/hr\text{-}ft^2$

g_m is the mass flux which is related to the shear stress on the interface, $lb_m/hr\text{-}ft^2$

B_m is the driving force which is obtained by the application of momentum equation, dimensionless

Methods for calculating the mass flux g_m and the driving force B_m will be discussed in turn.

Mass Flux

The momentum flux at a surface is defined as the mass flux at the surface times the tangential velocity at the surface. Thus, for the control volume enclosed by the G- and S-surfaces in Fig. 5,

(a) if the material entering through the S-surface has the tangential velocity u_S ft/hr, the corresponding momentum flux will be $\dot{w}''u_S$ $lb_m/ft\text{-}hr^2$

(b) if the material entering through the G-surface has

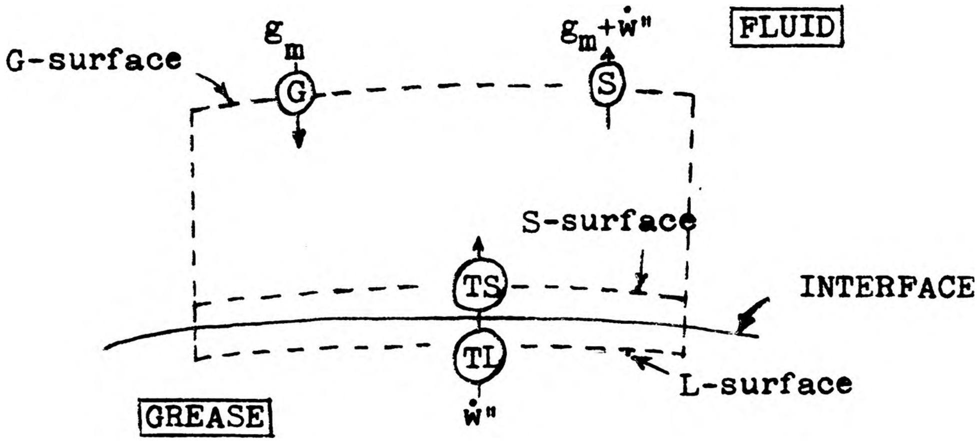

Figure 5. Control volume for momentum problem.

the tangential velocity u_G ft/hr, the corresponding momentum flux will be $g_m u_G$ $lb_m/ft\text{-}hr^2$

(c) if the material leaving through the G-surface has the tangential velocity u_S ft/hr, the corresponding momentum flux will be $(g_m+\dot{w}'')u_S$ $lb_m/ft\text{-}hr^2$.

The fundamental momentum equation states that the sum of the rate of change of momentum and the frictional resistance is zero when there is no pressure gradient in the direction of flow. Considering Fig. 5 and making a momentum flux balance on the system,

$$\dot{w}''u_S + g_m u_G - (g_m+\dot{w}'')u_S - \tau g_o = 0 \qquad ......(13)$$

where τ is the shear stress on the interface, lb_f/ft^2.
By rearranging Eq. (13),

$$g_m = \frac{\tau g_o}{u_G - u_S} \qquad ..... (14)$$

It will be noted that the material entering through the S-surface usually possesses no momentum in the flow direction tangential to the interface, because the tangential velocity is zero in the immediate vicinity of the interface. Hence $u_S = 0$ and Eq. (14) reduces to

$$g_m = \frac{\tau g_o}{u_G} \qquad ..... (15)$$

In order to obtain the value for the mass flux, g_m, in terms of measurable quantities, a new term, the friction factor, will be introduced by the following relation:

$$\tau = \frac{c_{fx}\rho_G u_G^2}{2g_o} \quad \text{..... (16)}$$

where c_{fx} is the friction factor in the flow direction parallel to the surface, dimensionless

ρ_G is the density of the fluid in the G-state, lb_m/ft^3

Substituting Eq. (16) into Eq. (15),

$$g_m = \frac{c_{fx}\rho_G u_G}{2} \quad \text{..... (17)}$$

This is the required equation for the mass flux. The only unknown in the equation is the friction factor, c_{fx}, the value of which depends upon whether the flow over the plate is laminar or turbulent. The following two empirical equations are suggested [11] to calculate the friction factor in each case:

For laminar flow,

$$c_{fx} = 0.664\ Re_x^{-1/2} \quad \text{..... (18)}$$

For turbulent flow,

$$c_{fx} = 0.0576\ Re_x^{-1/5} \quad \text{..... (19)}$$

where $Re_x = \frac{x u_G \rho_G}{\mu_G}$, Reynolds number, dimensionless

x = Distance from leading edge of the plate, ft

u_G = Velocity of the fluid flowing parallel to the plate, ft/hr

ρ_G = Density of the fluid, lb_m/ft^3

μ_G = Absolute viscosity of the fluid, lb_m/hr-ft.

Thus, by using Eq. (17) with Eqs. (18) and (19), the value of the mass flux, g_m, will be obtained.

Driving Force

As shown earlier, the general expression for the driving force is

$$B_m = \frac{P_G - P_S}{P_S - P_T} \qquad \text{..... (20)}$$

In order to obtain a particular expression for use in the present problem, it will be necessary to apply the momentum equation to the G-S volume. Accordingly, the net force on the control volume in the direction of the fluid jet is equal to the mass flow rate times the change of velocity, provided the frictional resistance to the jet is neglected. Considering Fig. 5, assuming unit surface area of the plate, and making the balance, the following equation will be obtained:

$$p_G g_m + p_{TS}\dot{w}'' - p_S(g_m+\dot{w}'') = \frac{\dot{a}V_G g_m}{g_o} + \frac{\dot{a}V_{TS}\dot{w}''}{g_o} - \frac{\dot{a}V_S(g_m+\dot{w}'')}{g_o} \qquad \text{..... (21)}$$

where p_G and p_S are the fluid pressures at the G- and S-surfaces, lb_f/ft^2

p_{TS} is the pressure of the transferred substance at the S-surface, lb_f/ft^2

$\dot{a}$ is the mass rate of flow through the nozzle, lb_m/hr

V_G and V_S are the fluid jet velocities at the G- and S-surfaces, ft/hr

V_{TS} is the velocity of the transferred substance at the S-surface, ft/hr.

Neglecting the smaller quantities p_{TS} and V_{TS}, and rearranging Eq. (21),

$$\frac{\dot{w}''}{g_m} = \frac{(p_G-p_S)g_o - \dot{a}(V_G-V_S)}{p_S g_o - \dot{a}V_S}$$

OR

$$B_m = \frac{(p_G-p_S)g_o - \dot{a}(V_G-V_S)}{p_S g_o - \dot{a}V_S} \qquad \text{..... (22)}$$

This is the required expression for the driving force.

Finally, by substituting proper values for the mass flux, g_m, and the driving force, B_m, from Eqs. (17) and

(22) into Eq. (12), the mass rate of removal $\dot{w}''$ can be easily calculated.

Again, some minor assumptions are made in the momentum theory analysis. They are as follows:

(a) In making the momentum flux balance on the control volume, it is supposed that there is no pressure gradient in the flow direction parallel to the surface.

(b) The tangential velocity is zero in the immediate vicinity of the interface.

(c) The frictional resistance offered to the impinging jet by the surroundings is negligible.

(d) The pressure and velocity of the transferred substance at the S-state are negligibly small.

Combining the results obtained from both the heat transfer theory and the momentum principle, the total rate of mass removal from the surface can be written as:

$$\text{Total mass transfer rate} = \dot{m}'' + \dot{w}''\ \mathrm{lb_m/hr\text{-}ft^2} \quad \ldots\ldots \quad (23)$$

RESULTS AND CONCLUSIONS

The analytical treatment has been made to investigate a method for predicting the total mass transfer rate of grease deposits caked on a flat surface.

It is seen from Fig. 6 that under any given conditions, the effect of increase in density of steam (cleaning fluid) is to decrease the mass removal rate due to heat transfer, $\dot{m}''$, but to increase the mass removal rate due to momentum transfer, $\dot{w}''$. However, the total mass transfer rate, $\dot{m}''+\dot{w}''$, is increased. The increase in temperature is indicated by the decrease in density of steam. The most suitable cleaning temperature should be determined from practical considerations of the type of material to be removed and the capacity of the cleaner.

The curves in Fig. 7 show the effect of the jet impingement angle on the three rates of mass removal. No definite effect of the angle is observed on the rate due to heat transfer. The rate due to momentum transfer as well as the total rate decreases with increase in the angle. The most suitable angle for a particular application should be determined from practical considerations. However, an angle of 4°-5° is recommended by some manufacturers of steam cleaning equipment.

Although the increase in velocity of steam causes decrease in the rate due to heat transfer, it greatly increases the other two rates, as shown in Fig. 8. High steam velocity causes friction and thereby definitely removes more material.

Illustrative examples showing the applications of the method, discussed in the analytical treatment, are included in the appendix. Superheated steam is used as the cleaning fluid.

The following conclusions may be drawn from the investigation:

(1) The rate of mass removal due to momentum transfer is always higher than the corresponding rate due to heat transfer.

(2) The temperatures at G-, S- and F-surfaces, the type of material to be removed, and the thickness of the material, all have great influence on the driving force for heat transfer theory.

(3) The driving force for momentum theory is mainly governed by the pressures at G- and S-surfaces.

(4) The most suitable jet impingement angle is 10° from horizontal, or less, depending upon practical situations.

(5) A high fluid velocity results into a high rate of mass removal.

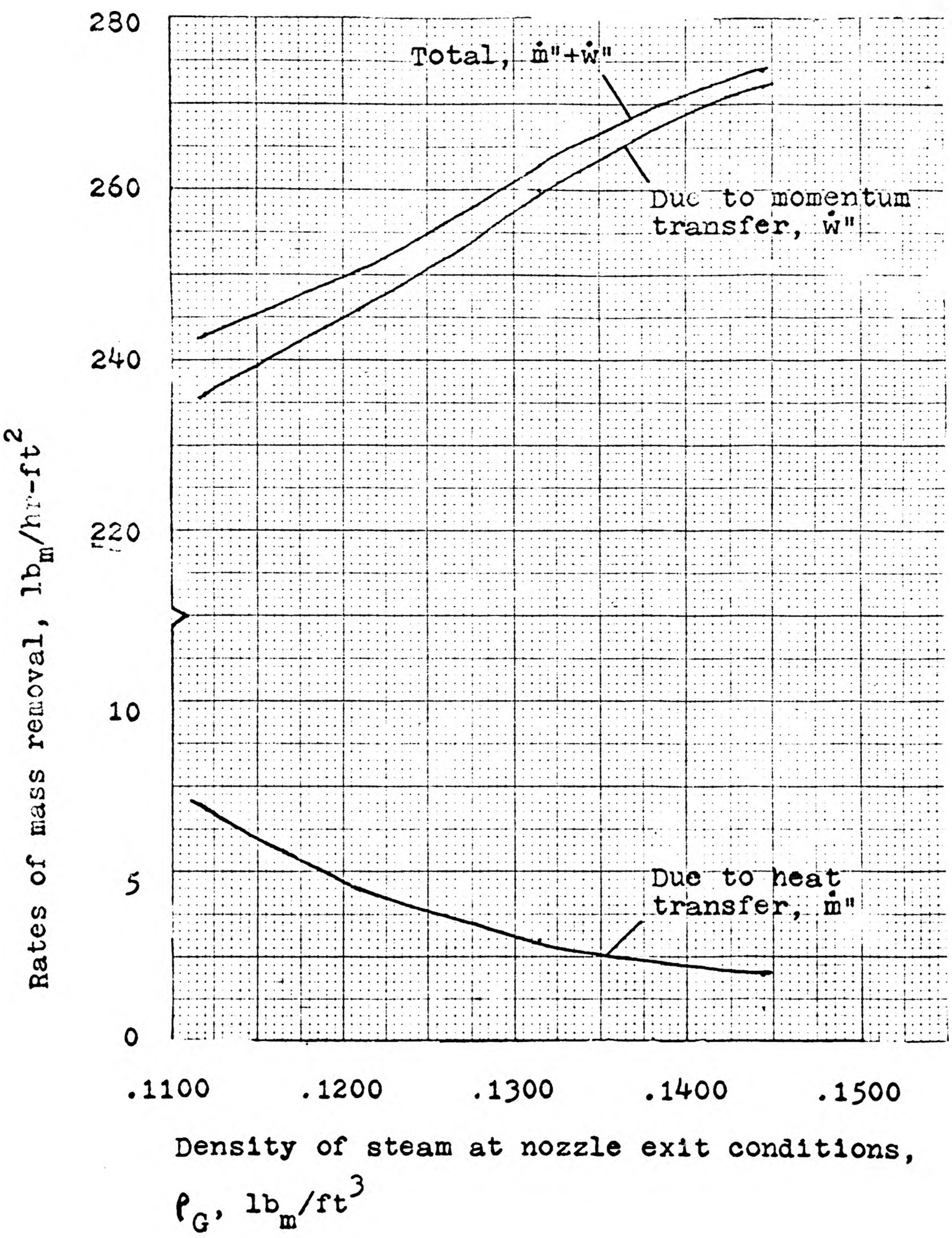

Figure 6. Effect of density of steam on the rates of mass removal.

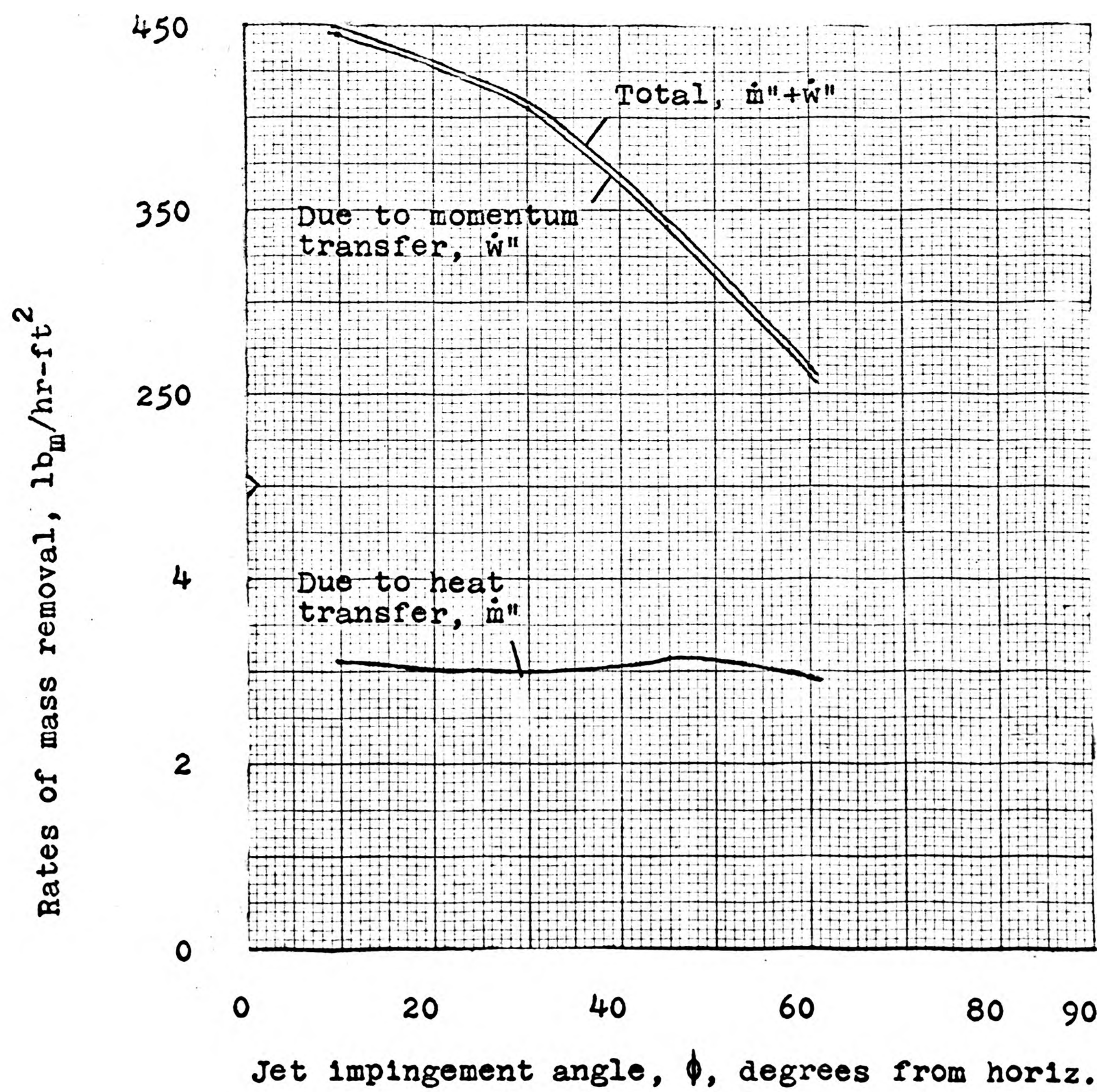

Figure 7. Effect of jet impingement angle on the rates of mass removal.

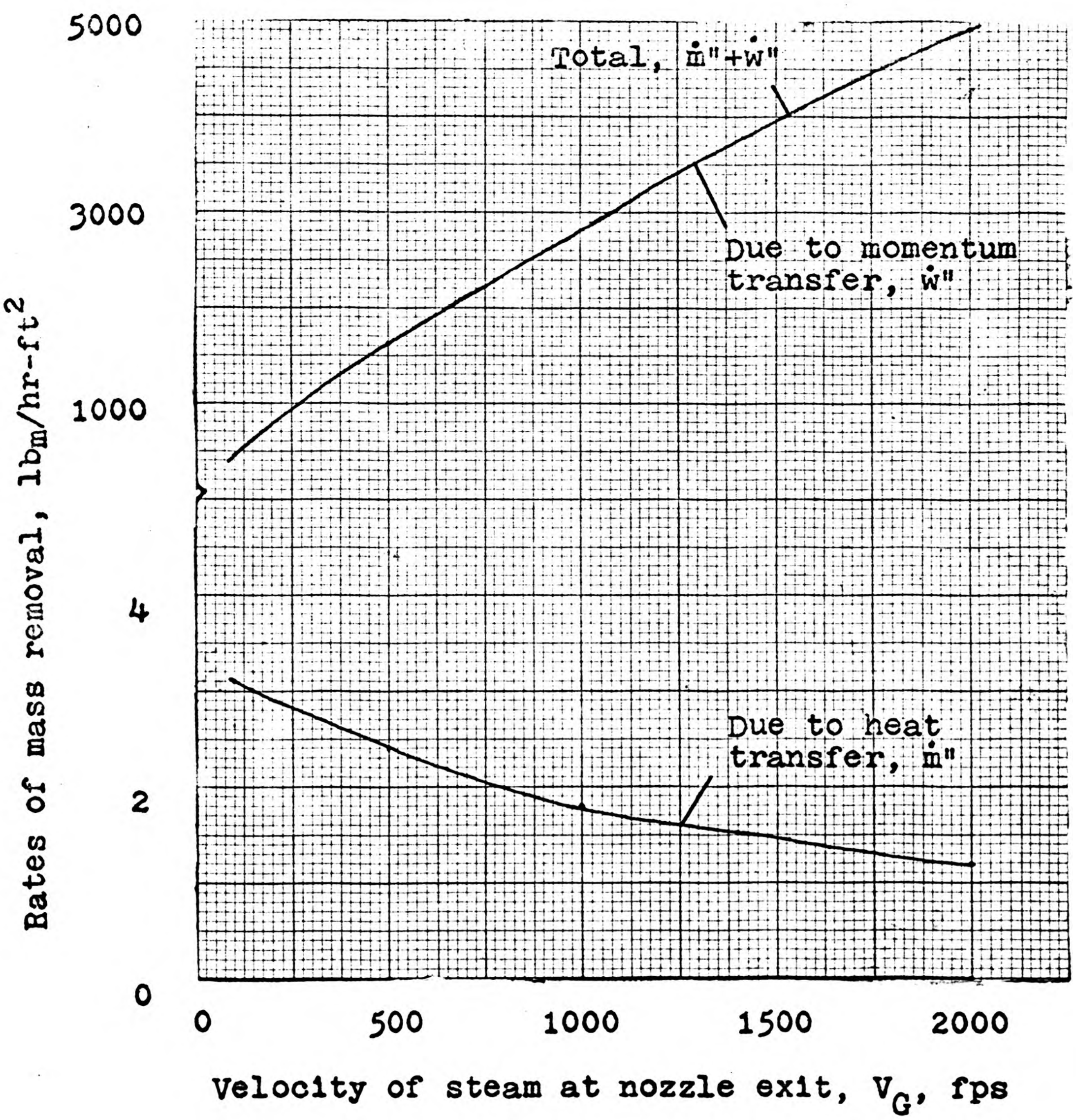

Figure 8. Effect of velocity of steam on the rates of mass removal.

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APPENDIX

The following examples will illustrate, for different practical cases, the method of calculating the total rate of mass removal of material caked on a surface.

Example 1

A jet of superheated steam is used to clean a flat horizontal plate caked with mud and grease. It is required to determine the total rate of mass removal from the plate when the temperature of steam at nozzle exit, t_G, is (i) 600° F (ii) 700° F (iii) 800° F (iv) 900° F. The following data are assumed to be known:

Exit diameter of steam nozzle	$= d = \frac{1}{4}''$
Distance from plate to nozzle	$= L = 8''$
Pressure of steam at nozzle exit	$= p_G = 90$ psia
Velocity of steam at nozzle exit	$= V_G = 100$ fps
Pressure of steam at S-surface	$= p_S = 14.7$ psia
Bulk temperature of transferred substance	$= t_F = 70^\circ$ F
Average specific heat of transferred substance	$= c_{PT} = 0.4$ Btu/lb$_m$-$^\circ$F
Average thermal conductivity of transferred substance	$= k_T = 0.0786$ Btu/hr-ft-$^\circ$F
Latent heat of vaporization of transferred substance	$= L_{vT} = 126$ Btu/lb$_m$
Thickness of transferred substance	$= \delta_T = 1''$

Jet impingement angle = ϕ = 60° from horizontal.

Solution

Properties of superheated steam at nozzle exit conditions of p_G=90 psia and t_G=(i) 600° F (ii) 700° F (iii) 800° F (iv) 900° F:

Density, lb_m/ft^3 = ρ_G =

(i) 0.1445 (ii) 0.1316 (iii) 0.1209 (iv) 0.1119

Thermal conductivity, Btu/hr-ft-$^{\circ}$F = k_G =

(i) 0.024 (ii) 0.027 (iii) 0.029 (iv) 0.032

Absolute viscosity, lb_m/hr-ft = μ_G =

(i) 0.048 (ii) 0.054 (iii) 0.058 (iv) 0.064

Specific heat at constant pressure, Btu/lb_m-$^{\circ}$F = c_{pG} =

(i) 0.515 (ii) 0.510 (iii) 0.510 (iv) 0.510

Enthalpy, Btu/lb_m = i_G =

(i) 1328.7 (ii) 1378.1 (iii) 1427.9 (iv) 1478.1

As stated earlier, the properties of a cleaning fluid at the G-state are the same as those at the nozzle exit conditions.

By using Eq. (4),

Heat transfer coefficient = h = (i) 31.95 Btu/hr-ft^2-$^{\circ}$F
(ii) 31.80
(iii) 31.00
(iv) 30.80

Substituting these values of h into Eq. (3),

Surface conductance = g_h = (i) 62.00 $lb_m/hr\text{-}ft^2$

(ii) 62.40

(iii) 60.75

(iv) 60.40

Since the corresponding temperature of steam at the S-surface, t_S, is not known, it will have to be determined from the known quantities.

$$B_h = \frac{i_G - i_S + \dfrac{V_G^2 - V_S^2}{2g_oJ}}{i_S - i_{TS} + \dfrac{V_S^2}{2g_oJ} - \dfrac{\dot{q}_S''}{\dot{m}''}} \qquad \ldots\ldots (11)$$

The terms $\dfrac{V_G^2 - V_S^2}{2g_oJ}$ and $\dfrac{V_S^2}{2g_oJ}$ are very small in this case and hence may be neglected. Using Eq. (1) and rearranging,

$$\dot{m}'' = \frac{g_h(i_G - i_S) + \dot{q}_S''}{i_S - i_{TS}}$$

Substituting $\dot{q}_S'' = h(t_G - t_S)$,

$$\dot{m}'' = \frac{g_h(i_G - i_S) + h(t_G - t_S)}{i_S - i_{TS}} \qquad \ldots\ldots (A\text{-}1)$$

The only unknown terms in the right hand side of Eq. (A-1) are t_S, i_S, and i_{TS}, the latter two being functions of t_S.

The enthalpy i_{TS} can be obtained by using the relation $i_{TS} = c_{pT}(t_S-32) + L_{vT}$.

Next, making an energy balance on the LS control volume of Fig. 4,

$$\dot{m}'' i_{TL} - \dot{m}'' i_{TS} = \dot{q}_L'' - \dot{q}_S'' \qquad \text{..... (A-2)}$$

Rearranging,

$$\dot{m}''(i_{TS}-i_{TL}) + \dot{q}_L'' = \dot{q}_S'' \qquad \text{..... (A-3)}$$

Since it is assumed that the thickness L-S is negligibly small, temperature equilibrium prevails between the S- and L-states, i. e. $t_S = t_L$. The enthalpy difference, $i_{TS} - i_{TL}$, in Eq. (A-3) is therefore the latent heat of vaporization of the transferred substance, L_{vT}. The heat flux $\dot{q}_L''$ is responsible for the enthalpy increment of and the conduction through the transferred substance.

Substituting $i_{TS} - i_{TL} = L_{vT}$

$$\dot{q}_L'' = \dot{m}'' c_{pT}(t_S-t_F) + \frac{k_T(t_S-t_F)}{\delta_T}$$

$$\dot{q}_S'' = h(t_G-t_S)$$

into Eq. (A-3) and rearranging,

$$\dot{m}'' = \frac{h(t_G-t_S) - \dfrac{k_T(t_S-t_F)}{\delta_T}}{L_{vT} + c_{pT}(t_S-t_F)} \qquad \text{..... (A-4)}$$

The only unknown term in the right hand side of Eq. (A-4) is t_S.

Writing Eqs. (A-1) and (A-4) together,

$$\dot{m}'' = \frac{g_h(i_G - i_S) + h(t_G - t_S)}{i_S - i_{TS}} = \frac{h(t_G - t_S) - \dfrac{k_T(t_S - t_F)}{\delta_T}}{L_{vT} + c_{pT}(t_S - t_F)} \qquad \ldots\ldots \text{(A-5)}$$

The equality of the second and third terms permits t_S to be found. Eq. (A-5) can be solved conveniently by graphical method. A curve is plotted with assumed values of t_S to satisfy Eq. (A-1). Similarly, another curve is plotted on the same graph paper to satisfy Eq. (A-4). The intersection point of the two curves satisfies both Eqs. (A-1) and (A-4), and gives, as its abscissa, the value of t_S which satisfies the equations; and as its ordinate, the corresponding value of $\dot{m}''$. The curves of Fig. 9 are plotted to obtain the values for t_S and $\dot{m}''$ when $t_G = 600^\circ$ F.

The following table is drawn up to plot the curves of Fig. 9:

TABLE I .....

TABLE I

t_S ^oF	500	525	550	575
i_S Btu/lb$_m$	1285.4	1297.3	1309.2	1321.1
i_{TS} Btu/lb$_m$	313.2	323.2	333.2	343.2
$\dfrac{g_h(i_G-i_S) + h(t_G-t_S)}{i_S - i_{TS}}$	6.05	4.46	2.88	1.30
$\dfrac{h(t_G-t_S) - \dfrac{k_T(t_S-t_F)}{\delta_T}}{L_{vT} + c_{pT}(t_S-t_F)}$	9.37	6.40	3.61	0.976

The results obtained from Fig. 9 are:

$t_S = 565^o$ F.

$\dot{m}'' = 1.93$ lb$_m$/hr-ft^2

Similarly, curves can be plotted to obtain the values of t_S and $\dot{m}''$ when t_G is 700^o F, 800^o F and 900^o F respectively. The results are as shown below:

For $t_G = 700^o$ F: $t_S = 650^o$ F and $\dot{m}'' = 2.93$ lb$_m$/hr-ft^2.

For $t_G = 800^o$ F: $t_S = 724^o$ F and $\dot{m}'' = 4.51$ lb$_m$/hr-ft^2.

For $t_G = 900^o$ F: $t_S = 785^o$ F and $\dot{m}'' = 6.90$ lb$_m$/hr-ft^2.

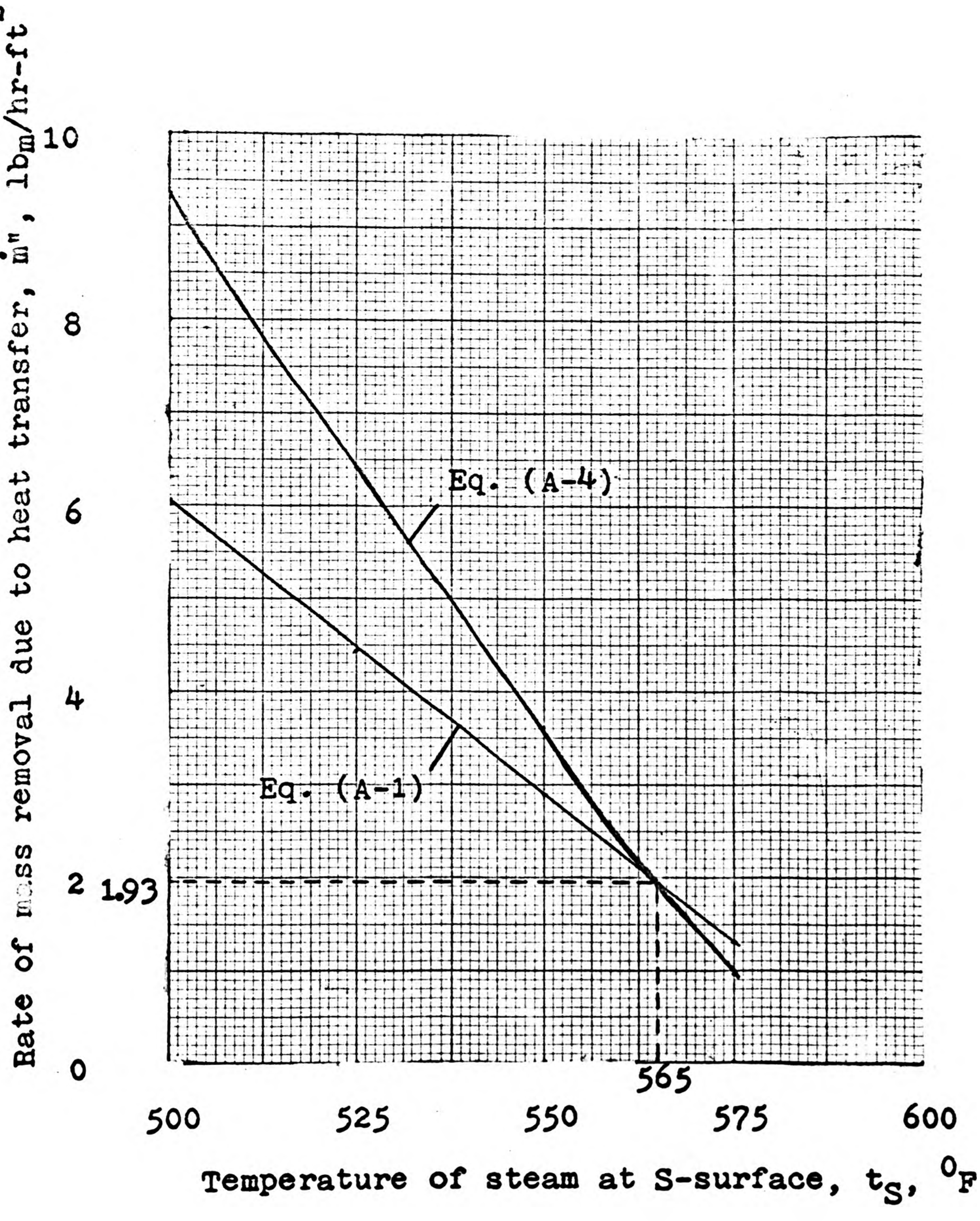

Figure 9. Graphical method to determine t_S and $\dot{m}''$.

After determining the rate of mass removal for the heat transfer process, $\dot{m}''$, the next step is to calculate the rate of mass removal for the momentum process, $\dot{w}''$.

In determining Re_x, the Reynolds number in the flow direction parallel to plate, the distance x is taken equal to 1 ft and the tangential velocity u_G is calculated by using the relation $u_G = V_G \cos \phi$.

The velocity of jet at the S-surface, V_S, can be obtained from the mass velocity, G, of the cleaning fluid.

$$G = \rho_G V_G = \rho_S V_S, \text{ from which } V_S = \frac{G}{\rho_S} = \frac{\rho_G V_G}{\rho_S}.$$

V_S is the striking velocity of the jet and is to be determined at pressure p_G and temperature t_S.

By using Eq. (19), Friction factor = c_{fx} =
(i) 0.004107 (ii) 0.004286 (iii) 0.004422 (iv) 0.004578

Substituting these values of c_{fx} into Eq. (17),

Mass flux for momentum theory = g_m = (i) 53.30 $lb_m/hr\text{-}ft^2$
(ii) 50.70
(iii) 48.10
(iv) 46.10

Using Eq. (22), the driving force = B_m = (i) 5.12
(ii) 5.12
(iii) 5.12
(iv) 5.12

Substituting the values for g_m and B_m into the fundamental Eq. (12), $\dot{w}'' =$ (i) 272 $lb_m/hr\text{-}ft^2$

(ii) 260

(iii) 246

(iv) 236

Finally, the total rate of mass removal from the plate is obtained by adding $\dot{m}''$ and $\dot{w}''$ as suggested by Eq. (23).

Total rate $= \dot{m}'' + \dot{w}'' =$ (i) 273.93 $lb_m/hr\text{-}ft^2$

(ii) 262.93

(iii) 250.51

(iv) 242.90

The results obtained from example 1 are tabulated below:

TABLE II

t_G °F	ρ_G lb_m/ft^3	$\dot{m}''$ $lb_m/hr\text{-}ft^2$	$\dot{w}''$ $lb_m/hr\text{-}ft^2$	$\dot{m}'' + \dot{w}''$ $lb_m/hr\text{-}ft^2$
600	0.1445	1.93	272	273.93
700	0.1316	2.93	260	262.93
800	0.1209	4.51	246	250.51
900	0.1119	6.90	236	242.90

The effect of the density of steam on the three rates of mass removal is shown graphically in Fig. 6.

Example 2

Example 1 is repeated with the following changes in the data:

Temperature of steam at nozzle exit = t_G = 700° F

Jet impingement angle = ϕ = (i) 10° from horiz.

(ii) 30°

(iii) 45°

(iv) 60°

Solution

The procedure of calculating the rates of mass removal is the same as that used in example 1. The results are tabulated in table III.

TABLE III

ϕ Degrees from horiz.	$\dot{m}''$ $lb_m/hr\text{-}ft^2$	$\dot{w}''$ $lb_m/hr\text{-}ft^2$	$\dot{m}'' + \dot{w}''$ $lb_m/hr\text{-}ft^2$
10	3.10	445	448.10
30	3.00	405	408.00
45	3.15	342	345.15
60	2.93	260	262.93

The effect of the jet impingement angle on the three rates of mass removal is shown graphically in Fig. 7.

Example 3

Example 1 is repeated with the following changes in the data:

Temperature of steam at nozzle exit $= t_G = 700^\circ$ F

Jet impingement angle $= \phi = 10^\circ$ from horiz.

Velocity of steam at nozzle exit $= V_G =$ (i) 100 fps

(ii) 500

(iii) 1000

(iv) 2000

Solution

It is assumed that Eq. (4) can be used for the range of velocities considered in this example. The procedure of calculating the rates of mass removal is the same as that used in example 1, except that the terms $\frac{V_G^2 - V_S^2}{2g_oJ}$ and $\frac{V_S^2}{2g_oJ}$ cannot be neglected for higher velocities. The results are tabulated below:

..... TABLE IV

TABLE IV

V_G fps	$\dot{m}''$ $lb_m/hr\text{-}ft^2$	$\dot{w}''$ $lb_m/hr\text{-}ft^2$	$\dot{m}'' + \dot{w}''$ $lb_m/hr\text{-}ft^2$
100	3.10	445	448.1
500	2.40	1620	1622.4
1000	1.80	2820	2821.8
2000	1.20	4920	4921.2

The effect of the jet velocity on the three rates of mass removal is shown graphically in Fig. 8.

VITA

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