THE RATE OF INTERACTION

BETWEEN

LIQUIDS AND GASES

Walter G. Whitman

Course   X

June 1, 1920

Thesis submitted to the Faculty

of the Massachusetts Institute

of Technology in partial fulfill-

ment of the requirements for the

Degree of Master of Science in

Chemical Engineering.

TABLE OF CONTENTS

GENERAL DISCUSSION

The problem of transferring either matter or energy from one phase to another is almost universally encountered in some form by the chemical engineer. The processes of boiling, evaporation, distillation, drying and many others depend upon heat transfer, while extractions, absorptions, and the like involve the transfer of matter. The purpose of this paper is to discuss a limited part of the general field outlined above, considering only those interactions which occur between liquids and gases.

Interaction between Phases

The industrial application of these interactions are important in a wide variety of industries. Gas absorption systems are employed to recover ammonia and light oils from coal gas, to produce sulphite and bleach liquors for the manufacture of paper, to remove carbon dioxide from flue gases in the production of liquid carbonic acid, and to recover volatile solvents after they have evaporated. Air conditioning by humidification or dehumidification, and the cooling of hot water by sprays or towers are other

Applications of Liquid-Gas Interactions.

processes involving the same essential
characteristics of transfer between
liquid and gas.   General relationships
should exist between these operations which
are all so similar in their nature and
the semi-theoretical discussion on page 17
suggests the probable similarities.

At present very little is known
about the design of gas absorption
equipment except regarding the performance
ances of actual installations in operation.
In other words it has been impossible to
design new equipment to handle new problems
and predict the results with any accuracy.
The main reason for this is that the
effect of various factors upon the absorption
has not been clearly recognized and that
engineers have considered merely the
performance figures from tests without
going back to the essential theory of
absorption.

Inadequate
Methods
of
Designing
Equipment

The performance of an absorption
machine is given in terms of the recovery
under definite conditions. For example,
a scrubber may be advertised as recovering
95% of the light oil from 100,000 cu.ft.
of coal gas per hour.   The initial light

oil content and the amount of scrubbing oil is usually given, but these figures are not sufficient to give a good estimate on the recovery if operating conditions are radically changed.

In the first place, none of the figured given is of itself a measure of the "efficacy" of the scrubber as an absorption machine.   The "95% recovery" can be considered as an estimate of performance, and yet it is well recog- nized that the percentage recovery varies enormously as other factors such as concentration of inlet gas, temperature, velocity of gas and amount of scrubbing oil are changed. Furthermore, the recovery figure gives no idea as to the efficiency of the scrubber, since the maximum theoretical absorption may vary anywhere from 0 to 100% and is definitely fixed by the operating conditions. 100% or perfect absorption is theoretically possible in a tower of infinite length or with infinite time of contact,while if the scrubbing oil were saturated with benzol when fed to the top of the tower no absorption could be realized. For this

Objections
to
Basing
Design
on
"Recoveries"

reason a given scrubber, operating on
two different processes, might recover
97% in one case and only 85% in another
and yet be performing its duty with the
same efficacy in both instances.
The difference in recoveries would then
be due solely to differences in operating
conditions.

Another objection to attaching
great significance to recovery figures
is evident when the recoveries attained
by different types of scrubbers operating
under similar conditions are compared.
An excellent tower might give 95%
absorption from a certain gas and yet the
poorest absorber would recover perhaps
80%.   This slight difference in recovery
figures is easily explained when it is
realized that the difficulties of
absorption really begin when the
concentrations of gas to be absorbed be-
come low.   And yet, as a matter of
visualization, it is difficult to estimate
the relative efficacies of two pieces
of equipment when the recovery figures
in which the estimate is based vary so
slightly in magnitude.

It is possible, however, to make comparison between absorption machines which will be independent of the operating conditions of the test runs. The method of accomplishing this consists merely in determining the rate of absorption and from this a so-called "absorption coefficient." The latter term is merely the rate of absorption under unit conditions and will be explained in detail later on. It is entirely analogous to the coefficient of heat transfer used in problems in the flow of heat, and can be used as a direct estimate of the value of any machine as an absorber.

The
Rate
of
Absorption.

THE RATE OF INTERACTION

The rate of transfer of energy or of matter from gas to liquid or vice versa is determined by the same general laws as apply to the rate of heat-flow and of electrical flow.* Under any definite set of conditions these systems tend to come to conditions of equilibrium

Equilibria
and
Rates
of
Reaction

* The rate of chemical reaction is also proportional to the distance from equilibrium, but the mathematical expressions in this case are frequently complicated.

and the rate at which they approach
equilibrium at any time is proportional
to the difference between conditions at
that time and the equilibrium conditions.
The driving force or potential of the
reaction is determined by the distance
from equilibrium; in heat flow it is the
temperature drop and in electrical flow
the voltage drop.

In the discussion of gas
absorption systems a simple nomenclature,
$\qquad\qquad\qquad$ of that $\qquad\qquad$ (1)
a modification ‸suggested by Lewis,
will be introduced. The material to be
absorbed is the solute, the inert gas
which brings it into the system is the   Nomenclature
carrier, and the absorbing liquid is
the extractor. Concentrations of
solute in the liquid extractor are de-
noted by X; in the carrier it is simplest
to use a term proportional to the
concentration, namely, the actual pressure
of the solute in the gas, P or p.

Equilibrium is reached in gas
absorptions when the liquid extractor is
saturated with solute at this pressure P
which the solute has in the gas at that
point. On the other hand, if the

extractor is not saturated with solute,

absorption takes place and the tendency

is to establish a condition of equilibrium.

The driving force tending to cause

absorption is measured by the difference

between P, the pressure of solute in the

gas, and p, the equilibrium or saturation

pressure over the liquid extractor whose

concentration is X, p, which is some-

times called the back pressure of the

liquid, is a function of X and frequent-

ly Henry's Law, i.e., p = ax, can be

applied, "a" being a proportionality

constant derived from direct measurements.

The driving force or potential is,

therefore, (P-p) which is frequently

written as Δ p.   The rate of absorp-

tion may now be written

$$\frac{dW}{d\theta} = \propto (P-p) = \gamma \Delta p$$

dW is the amount of material absorbed in

the time dθ when the driving pressure

is (P-p), and $\propto$ is a proportionality factor.

Before discussing the other factors which

influence the rate of absorption, it is

advisable to visualize the interaction

between gas and liquid as it occurs

when a drop of liquid is suspended in a

gas.

Driving
Pressure
or
Potential
Differences

The passage of any given substance
through a liquid or a gas is carried on
by two processes of diffusion of the
substance through the fluid and con-
vection in the mass of fluid itself.
These two processes are also instrumental
in the transfer of heat, although here a
third influence, that of radiation, must
also be considered.   The effects of
diffusion and convection are illustrated
in the following example. Assume a
porous wall of appreciable thickness
separating two chambers, the first of
which contains air and the second air
and ammonia gas.   In the second chamber
ammonia will be quickly and evenly
distributed throughout the space by con-
vection currents.   Since the separating
porous wall freely permits the passage
of gas, ammonia will travel through it
into the first chamber. But in this
case the gas normally held in the pores
of the wall is not free to move in
currents, convection is absent, and as
a result the ammonia passes through the
wall only by the relatively slow process
of diffusion through stationary gas by
molecular motion.   Once on the other

Diffusion
and
Convection

side of the wall, it is rapidly

distributed throughout the first chamber

by convection currents. If a plot be

constructed showing the concentrations

of ammonia in the gas at any time during

the transfer against its location

in the chamber or wall, the concentrations

would be uniform in each of the chambers

but a considerable concentration gradient

would be observed in the wall. From

this it is evident that, since the

processes of convection are

generally so much more rapid

than those of diffusion, the

resistance to the passage of

ammonia through the system is almost

entirely caused by the gas layer where

convection currents are absent.
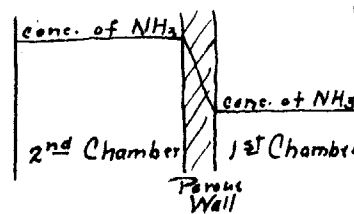
It has long been recognized

that a solid in contact with a fluid

retains on its surface a film of the fluid,

a film which is not truly stationary but   **Fluid**

which nevertheless is not subject to con-   **Films**

vection currents such as obtain in the

main body of the fluid. This film is

not of a definite thickness; its inner

face against the solid surface is

practically stationary, but from this

limit motion increases in the fluid
the further it is from the wall, so that
it quickly assumes the velocity of the
convection currents when a short
distance from the solid. The phenomenon
is illustrated by water flowing through
channels - the lowest velocity is found
nearest the walls and bottom, the highest
is reached at points furthest from the
bounding surfaces. Text books on the flow
of heat recognize this surface film effect
through which the diffusion of heat
is very slow,resulting in great resistance
to the passage of heat and high
temperature drops.

The same concepts apply in cases
where liquids and gases are in contact,
whether as drops, bubbles or comparatively
stationary surfaces. If a drop of liquid
be suspended in a gas two surface films
will exist. The gas may be in turbulent
motion as a whole, but close to the drop
a thin layer of gas will adhere to the
liquid and not be subject to convection.

Similarly, the inside of the liquid may be in motion, but at the surface there will be found a thin layer of liquid whose motion relative to its surrounding gas film is very slight. Exchange of material or of heat between gas and liquid must take place through the mass of gas, through these two films, and through the mass of liquid, or in other words, through four resistances arranged in series.

Importance of Film Resistances

Since these four resistances are encountered in series, the total resistance is the sum of the separate resistances; therefore, if any of the resistances be very small relative to the others it may be neglected in summation. It has just been shown that the two resistances in the main fluid bodies are slight because of convection currents which rapidly distribute matter or energy throughout the fluid. This means that they can be neglected in the discussion and the whole question of exchange now simplifies to a consideration of diffusion through liquid and gaseous films.

The laws governing electrical and
thermal flow are equally applicable to
diffusion phenomena through fluid films.
Briefly, the rate at which any material
will diffuse through a fluid film is
proportional to the area of the film and   Diffusion
                                                Formula
to the driving force or potential gradient,
terms whose significance has already been
explained. It is frequently impossible
to determine the contact area between
liquid and gas in an absorption machine
even approximately, but it is entirely
reasonable that this would be proportional
to the volume of the machine in most
cases. As a result the volume is
substituted for the actual area of con-
tact, and the resulting expression for
the rate of diffusion through a fluid
film is

$$\frac{dW}{d\theta} = BV\ (P-p)$$

This rate expression, differs from the
previous one only in the substitution of
B, a new proportionality factor and
V, the volume of equipment for $\propto$.
B, the proportionality factor, is a
term which varies with the conditions
of operation and whose characteristics

must be determined. It may be defined
as the rate of absorption per unit
volume and per unit of driving pressure
and is called the coefficient of
absorption, or in general, the transfer
coefficient.

FACTORS AFFECTING THE TRANSFER COEFFICIENT

A careful study of many types of
absorption equipment has resulted in the
following generalities concerning the
value of B. First; the value of B is
greatly influenced by the design of the
absorption machine; in fact the absorption
coefficients obtained for various
equipments are a direct measure of their
efficacy as absorbers per unit of volume.
The variation of B with design is so
great that the effect of other factors
must be studied by comparing a series
of runs all made on the same machine.
Gas velocity relative to the liquid has
a marked influence upon B because the
film resistances to diffusion are re-
duced when the tearing or brushing action
of moving gas thins down the effective
thickness of the film. Liquid
velocities cannot generally be varied

Factors
affecting
B

over wide ranges,but increasing the
amount of liquid in the system within
limits increases the area of surface
exposed. Temperature undoubtedly
influences the transfer coefficient,
since at higher temperatures the
molecules diffuse more rapidly.
Furthermore, the character of the
liquid,especially as regards its vis-
cosity,must make a great difference
although nothing definite is known about
this effect as yet. The effects of
gas velocity and of rate of flow of
water will be discussed more in detail.
Gas velocity past the liquid is
usually the principle factor affecting
B in any definite machine. The effect
of gas velocity relative to the liquid
should be somewhat the same in all
types of apparatus, but the effect of
velocity past the walls of the machine
is not directly concerned. On the other
hand, this latter velocity is the one
which is measured, and hence its effect
should vary with the design. For
example, the water in a packed tower is

held by the packing and is not picked
up by the gas as a spray to any extent.
In a spray chamber. however, increasing
the gas velocity increases liquid
velocity as well, so that velocity of
gas relative to liquid is not increased   Effect
of
in proportion with the increase in   Gas
Velocity
velocity past the walls. It would
therefore, be expected that gas velocity
as actually measured should influence
B more in coke towers than in spray
chambers. Boiling cap bubblers are
somewhat between these two limits of
design in that the interaction is with
liquid on the plate and also with spray
above the plate.

The nature of this velocity
function can be predicted in a general
way from a knowledge of gas velocity
effects in heat transfer from gases to
solids. The coefficient of heat   Velocity
Effect
transfer from gas to pipes has been   a
Power
carefully determined by a number of   Function
investigators,and Nusselt (2), Weber
(3) and Beckett (4) have decided that it
is best expressed as a power function
of the velocity through the pipes. The
same general relationship holds for

for water in pipes, and it seems
reasonable that a power function should
be satisfactory for absorption equipment.

Increasing the water feed to a
packed tower or spray should increase the
area of contact almost proportionately
up to a point where the packing surface
is covered in one case or the maximum
number of drops has been reached in the
other. Beyond this point an increase
in water flow should have very little
effect, since excess water would merely ~~surely~~
flood the tower or in the spray chamber and
would cause the formation of larger
drops without increasing the actual
number of unit droplets.

Effect
of
Rate
of
Flow
of
Liquid

The two important operating
factors on the gas side of absorption
units are the coefficient of
absorption, B, and the friction drop
through the tower. It is essential
that this latter be kept fairly low
when large volumes of gas are to be
handled. The relationships between
gas velocity, absorption coefficient
and friction drop are, therefore, of
great importance. It is well known
that the friction drop for gases in

turbulent motion is a power function of

the velocity, a function which

approximates 1.7 in pipes but which is

generally figured as 2. If friction drops

through absorption machines are also

Friction
Drop

power functions of the velocity

it should follow that B and the friction

drop are also connected by a power term, *i.e.*,

$$\text{Friction drop} = cB^n$$

Exact knowledge of the terms in this

equation would make it possible to calcu-

late the optimum gas velocity to be

attained in designing an absorber for any

specific purpose.

The relationship between the diffusion

of heat energy and that of matter through

the stationary gas film can be shown in

several ways, one of the easiest being

Relationship
between
Heat Transfer
and
Absorption
Coefficients.

to consider the operations occurring

in an adiabatic humidifier. (5)

In this equipment air is humidified

by contact with a spray of water which

is recirculated through the system, no

heat being received or lost from the

apparatus except through the air or

make-up water. It is obvious that the

water will soon reach a temperature at

which the heat given up to it by the air

---

lb. of air and $\overset{M}{N}$ lbs. of moisture)

by s

    r d M = -s d T

Integrating, on the assumption that r and

s are constant over the short temperature

range in question

$$M = - \frac{sT}{r} + \text{const.} \quad (1)$$

A second expression may be developed by

equating the rate of heat transfer from

air to the rate of heat loss from the

water caused by evaporation, since the

liquid remains at constant temperature.

The rate of heat transfer from the air

is

$$\frac{dQ}{D\theta} = h \ A \ (T-t) \quad (2)$$

where dQ heat units diffuse in the time

dθ, A is the area of the drop film, (T-t)

is the driving temperature potential,

and h is the coefficient of heat transfer.

    The rate of heat loss from the water

by evaporation is

$$\frac{dQ}{d\theta} = k' \ A \ (p-P)r$$

where p is the vapor of pressure of water

at temperature, t, i.e., the vapor

pressure of water from the liquid inside

the film, and P is the vapor pressure

of water in the air outside the film.

Derivation

  of

$\frac{h}{k} = s$

(p-P) is, therefore, the driving pressure

potential of diffusion and k' is a

diffusion coefficient. For this discussion

the term (m-M) will be substituted for

(p-P), introducing * only a slight error.

The modified expression then becomes

$$\frac{dQ}{d\theta} = k\ A\ (m-M)r \quad (3)$$

Equating (2) and (3)

$$h\ A\ (T-t) = kA\ (m-M)r \qquad m-M=\frac{h}{kr}\ (T-t)$$

$$M = m - \frac{h}{kr}\ (T-t) =$$

$$m - \frac{h}{kr}\ T + \frac{h}{kr}\ t \quad (4)$$

The two essential equations for M, (1)

and (4), must obviously be identical.

Therefore, $-\frac{sT}{r} + const = m -\frac{h}{kr}\ T + \frac{h}{kr}\ t$

Since T is not a function of m or t,

two conclusions can be drawn from the

mathematical nature of this equation.

The first is that $m + \frac{h}{kr}\ t$ is a

constant; this necessitates, since m

* The relation between (p-P) and (m-M)
is as follows: $M=\frac{P}{760-P}\ x\ \frac{18}{29}$
and $m = \frac{p}{760-p}\ x\ \frac{18}{29}$ If P and p are small
compared to 760 mm, as is almost always the
case, the error of substitution is very slight.

increases with t, that both m and t
remain constant, or in words that the
temperature of the water cannot change
in the process. This is, of course,
the first assumption used in figuring
the above equations.

The second and vital conclusion
is that $\frac{h}{kr}$ T equals $\frac{sT}{r}$ or that $\frac{h}{k}$ = s.
Expressed in another way, the coefficient
of heat diffusion divided by the
coefficient of diffusion of water equals
the humid heat of the gas mixture.
It is obvious that h and k must be
expressed in units as given above
for this relationship to hold.
The significance of this relationship
is extremely important and the limits
of its applicability must be investigated.
It really means that the performance of
any machine as an absorber can be pre-
dicted from its performance when used
for heat transfer. Obviously the
possibility of doing this would reduce
absorption and heat transfer to a common
basis and allow of their treatment as
parallel phenomena.

Significance
of
$\frac{h}{k}$ = s

EXPERIMENTAL RESULTS

The data available for calculating
the absorption or heat transfer coefficients
in various types of equipment has been obtained
chiefly.from work done at the Massachusetts   Equipment
                                                    Studied
Institute of Technology. The types of equip-
ment studied include coke towers, glass bubblers,
plate columns with slotted boiling caps,
centrifugal oil spray chambers, spray nozzle
chambers and spray cooling towers.

The rate of absorption in packed towers
was studied by Kenney (6)·and Stewart (7).
Kenney absorbed sulphur dioxide in water, and
Stewart absorbed carbon dioxide in caustic
solution in the same equipment. The
significance of their results was not realized
at the time of their theses but Lewis (1)
later discovered that the absorption coefficient
for either case was a power function of the
gas velocity, a function which he
approximated as two. It was further found
that the absorption coefficient for SO_2 was
really the same as that for CO_2 if
multiplied by a suitable factor deducted
from the molecular weights of the solutes and
carriers.   The data, however, was not
sufficiently accurate to justify definite

conclusions as to the effects of gas

velocity and the natures of the gases.

Keats (§) studied the operation of a

packed tower as a dehumidifier and obtained

accurate values for heat transfer coefficients

under definite conditions.   A tower 12 inches

in diameter was filled with carefully selected

three inch coke for 5'4", hot saturated air

was blown in at the bottom, and cold water

fed in at the top.   The results of his runs

to determine the effect of air velocity on

the coefficient of heat transfer are shown in

Plot I, and the equation $h = 0.109 V^{1.47}$

is seen to fit the experimental points very

closely.   This high power function of

1.47 checks qualitatively with the results

of Kenney and Stewart. Keats' results on

the effect of water velocity, Plot 2,

were meagre, but a hyperbolic curve seems

most suitable and is in line with the

theory outlined on page 16.   Three runs made

at varying temperatures (not shown) gave

coefficients which could be emperically connected

by assuming h proportional to the
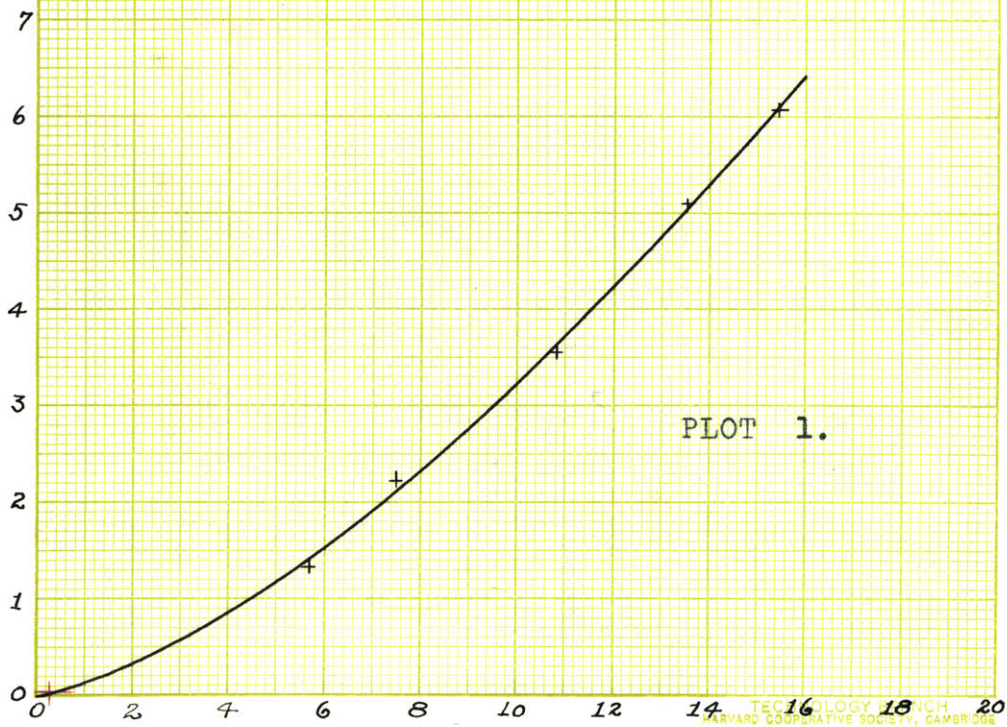
temperature in degrees Fahrenheit raised

to the 1.9 power.

EFFECT   OF   GAS   VELOCITY

ON   THE   COEFFICIENT   OF   HEAT   TRANSFER

IN   A   COKE-FILLED TOWER

Ordinates - Heat Transfer Coefficients,
            in B.T.U. per min. per ft.
            per ° F

Abscissae - Air velocities in lbs. of
            dry air per minute.

Equation of Curve - $y = 0.109 \; x^{1.47}$

PLOT 1.
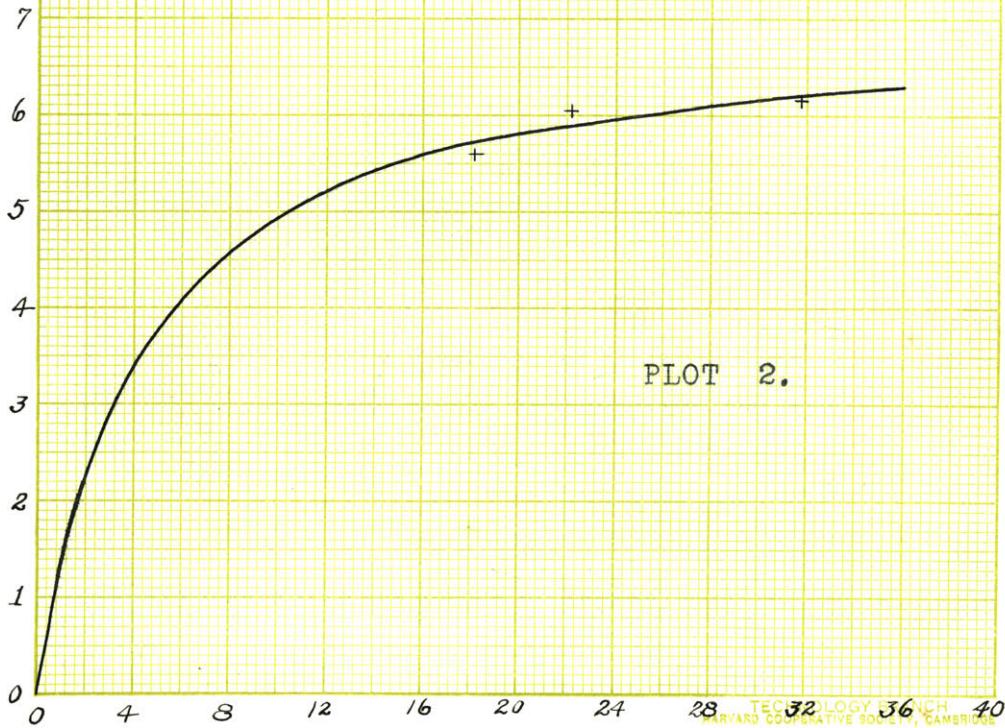
EFFECT   OF   RATE   OF   WATER   FLOW

ON   THE   COEFFICIENT   OF   HEAT   TRANSFER

IN   A   COKE-FILLED   TOWER

Ordinates - Heat Transfer Coefficients,
            in B.T.U. per min. per cu.ft.
            per ° F.

Abscissae - Lbs. of Water fed to Towers
            per minute.

Equation of Curve - $y = \dfrac{7.10 \; x}{x + 4.5}$

PLOT 2.

In this connection it is interesting to note that Tobin and Mosscrop (7) working on the absorption of CO_2 from a 14% gas with sodium carbonate solution, operated with a tower similar to that used by Keats. They used very low velocities and obtained a coefficient of absorption of.008 lbs. of CO_2 per cu.ft. per minute with a driving pressure of one lb. of CO_2 per lb. of air. The velocity in lbs. of air per minute was only about 2% of the maximum used by Keats, i.e., about 0.3 lbs. of dry air per minute. Recalculating this absorption coefficient over to heat transfer by the expression $\frac{h}{k} = s$, s should be about .274. h, therefore, equals k x s or about 0.0022. This point is shown in red in Plot I and lies right on the curve expressing Keats' results. Comparing this figure numerically with the value given by the formula $h = 0.109 V^{1.47}$, the latter is.0186 so that the check is within 16%.

Absorption
of
CO_2 in a
Coke
Tower

Plots 3 and 4 show the friction drop through Keats' tower plotted against the air velocity and h respectively. The friction drop is proportional to $V^{2.37}$ and to $h^{1.61}$; in other words the friction drop increases more rapidly than h does as the velocity is

RELATION BETWEEN

PRESSURE DROP AND GAS VELOCITY

IN A COKE-FILLED TOWER

Ordinates - Pressure Drops in inches of
water. Coke column 5 ft.4 in.
high.

Abscissae - Air Velocities in lbs.of dry
air per minute.

Equation of Curve - $y = 0.00817 \ x^{2.37}$

PLOT 3.
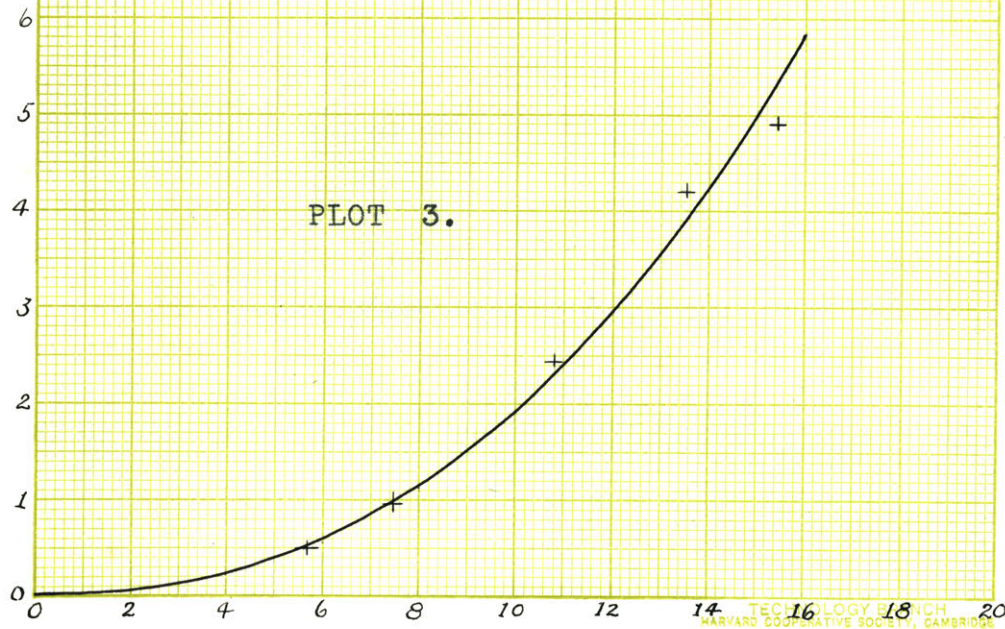
RELATION   BETWEEN   PRESSURE

DROP   AND   THE   HEAT   TRANSFER   COEFFICIENT

IN   A   COKE-FILLED   TOWER

Ordinates – Pressure Drops in inches of
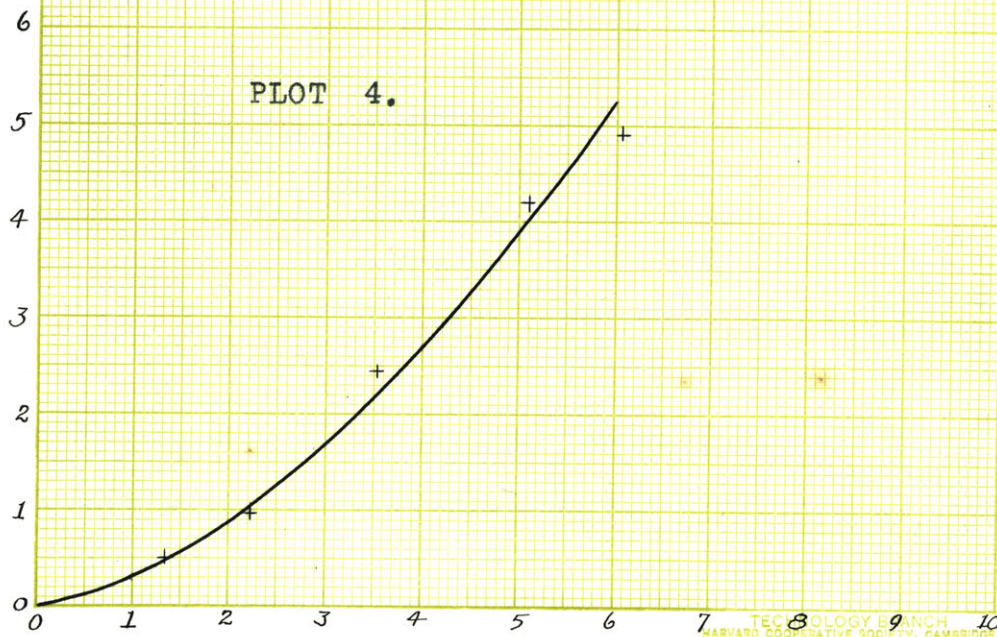water. Coke column 5 ft. 4 in.
high.

Abscissae – Heat Transfer Coefficients
in B.T.U. per min. per cu. ft.
per °F.

Equation of Curve – $y = 0.283 x^{1.63}$

PLOT   4.

raised.   From this relationship a coke
tower could be designed to give the proper
air velocity for optimum operation if the
economic conditions were known.   Since it
seems altogether probable that gas absorption
and heat transfer are parallel phenomena,
the equation connecting k and friction drop   Friction
in a coke tower should be of the same form as   Drop
above, namely: friction drop $= c\ k^{1.61}$.
It is proposed to continue work with this same
tower functioning as a humidifier and as a
gas absorber.   In this way it is hoped to
obtain absolute proof of the direct ratio
existing between heat transfer and gas
absorption referred to on page 21, i.e.,
that $\dfrac{h}{k} = S$.

Carlson and Harrop (10) studied the
absorption of ammonia from air with water
in a glass laboratory bubbler and found that
k varied directly as the first power of the   Absorption
                                                     in
air velocity.   They further determined that   Glass
                                                   Bubbler
k was apparently unaffacted by varying the
concentration of ammonia in the air.   This
latter would naturally be expected, since
any variability in concentration should cause
a corresponding variation in the driving
pressure and not affect the coefficient of
absorption.

Reynolds and Sanders (///) continued
a series of investigations started by the writer
on the absorption of ammonia from air by
water in a plate column equipped with slotted
boiling caps.   They performed about 130 runs
and obtained data which checked closely with
the formula

$$k = c V^{0.9}$$

with constant water velocity and water level
on the plates.   The effect of varying the
flow of water was almost negligible, but
increasing the depth of liquid on the plate
increased k greatly up to a certain depth:
due to the increased time of contact between
gas and liquid.

Absorption
with
Boiling
Caps

[handwritten marginal note: Note: R+S made a mistake in theory when computing the coeffs with different depths of liquor. The coefficients when calc. correctly, do not show any variation with depth (between 1½ & 4 inches, the range studied.) W.J.W.]

SPRAY CHAMBER

The writer was permitted the use of
some unpublished data on the operation of a
centrifugal spray chamber in two series of
tests.   The first series of about 35 runs
was made to determine the chamber's perform-
ance when cooling hot condensor water with
air.   The second series of 12 runs was
made on its operation as an absorption
machine for removing ammonia from air.

Centrifugal
Spray
Chamber
for
Heat
Transfer
and
Absorption

From the data thus obtained coefficients
of heat transfer and of ammonia absorption
have been calculated.   It was evident that

the first set of data on cooling hot water

was much more reliable than that obtained

by the absorption tests, so series one was

investigated to determine the effect of air

velocity,rate of flow of water, and

temperature on the heat transfer coefficient.

Air velocity exerted the most marked influence

(see plot no. 5), water flow had some effect

(see plot no. 6) and increasing temperature

evidently increased the coefficient. The

general formula which contains all these

functions is

$$h = c \, V^{0.65} \, \frac{W}{W + 0.8} \, t \qquad *$$

Centrifugal
Spray
Chamber
for
Heat
Transfer
and
Absorption

It will be noted that the velocity power of

0.65 is the lowest which has been obtained

from the tests just discussed.

The ammonia runs were made at

essentially constant temperature and rate

of water flow. The experimental error was

considerable for these runs, and the method

employed in calculating air velocity was

undoubtedly very inaccurate. On the plot

of k, the absorption coefficient, against

air velocity, a 0.65 power curve has been

* Units are arbitrary because of the confidential
nature of the original data.

EFFECT OF GAS VELOCITY

ON THE COEFFICIENT OF HEAT TRANSFER

IN A SPRAY CHAMBER

Ordinates - Heat Transfer Coefficients,
    corrected to a common temperature
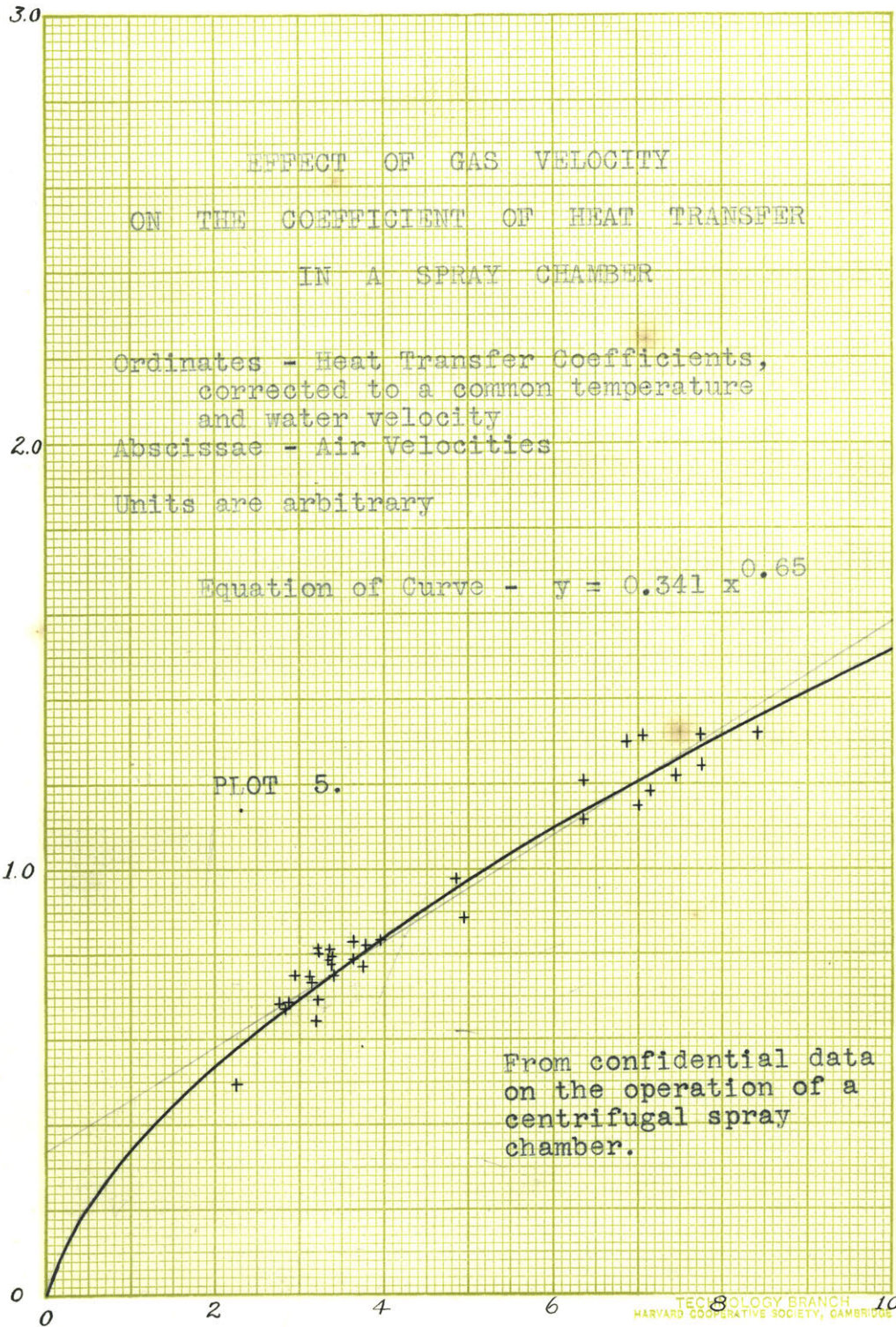   and water velocity
Abscissae - Air Velocities

Units are arbitrary

Equation of Curve - $y = 0.341 \, x^{0.65}$

PLOT 5.

From confidential data
on the operation of a
centrifugal spray
chamber.

3.0

2.0

1.0

0

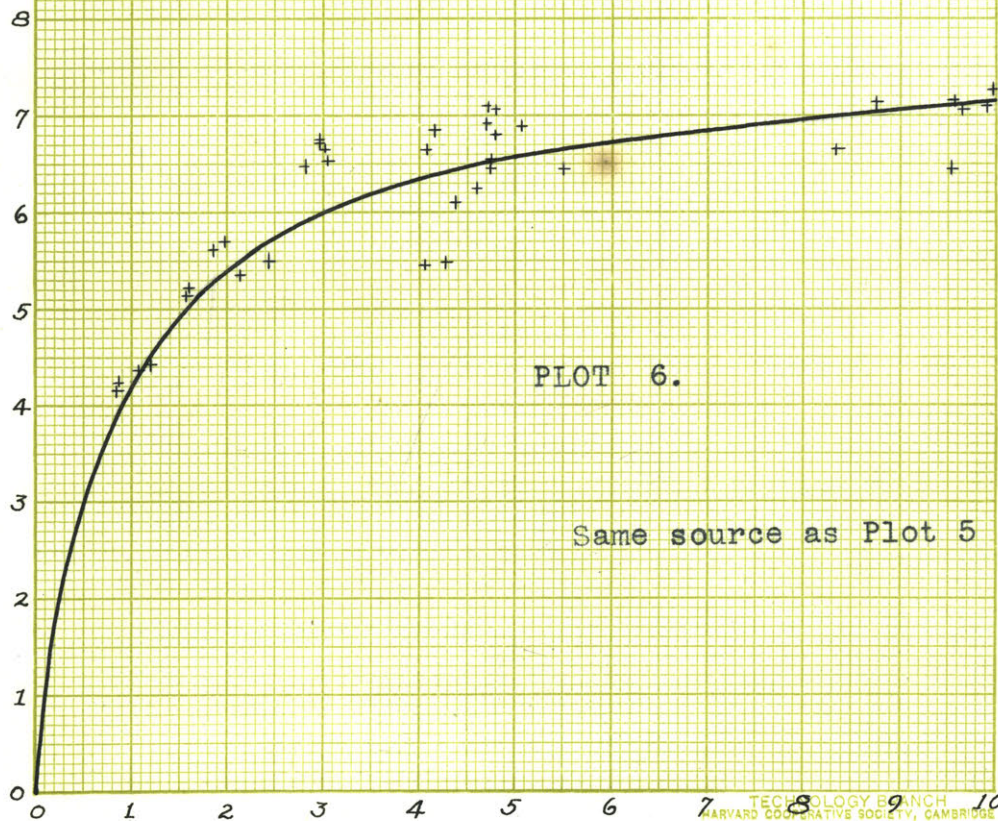0   2   4   6   8   10

EFFECT   OF   RATE   OF   WATER   FLOW

ON   THE   COEFFICIENT   OF   HEAT   TRANSFER

IN   A   SPRAY   CHAMBER

Ordinates – Heat Transfer Coefficients,
    corrected to a common temperature
    and air velocity
Abscissae – Rate of flow of water

Units are arbitrary

Equation of $y = \dfrac{7.70x}{x + 0.80}$

PLOT   6.

Same source as Plot 5

constructed because air velocity should
have the same effect here as it had in
series 1. It is evident that this curve
fits the points as well as could be expected
from the scattering.

These two series of runs offer an
excellent chance for checking or disproving
the theory outlined on page 21 which
states that $\frac{h}{k} = s$. Accordingly h and k
have been calculated for the same conditions
of air velocity, water flow and temperature.
h was expressed in B.T.U. per cu.ft. per
minute with a driving potential of 1° F.,
and k in lbs. of ammonia per cu.ft. per
minute with a driving pressure of 1 lb. of
ammonia per lb. of air. $\frac{h}{k}$ should equal s,
the specific heat of 1 lb. of dry air plus
the heat capacity of the ammonia in it;
this is about 0.25. Actually the calculations
gave $\frac{h}{k} = 0.17$ which is a 32% deviation
from the predicted value. This check was
unexpectedly close and indicates the
probable validity of the relationship/

Check on
$\frac{h}{k} = s$

EFFECT   OF   GAS   VELOCITY

ON   THE   COEFFICIENT   OF   AMMONIA   ABSORPTION

IN   A   SPRAY   CHAMBER

Ordinates - Absorption Coefficients
           (runs at same temperature and
            water velocity)

Abscissae - Air Velocities

Units are arbitrary

Equation of Curve - $y = 1.90\ x^{0.65}$

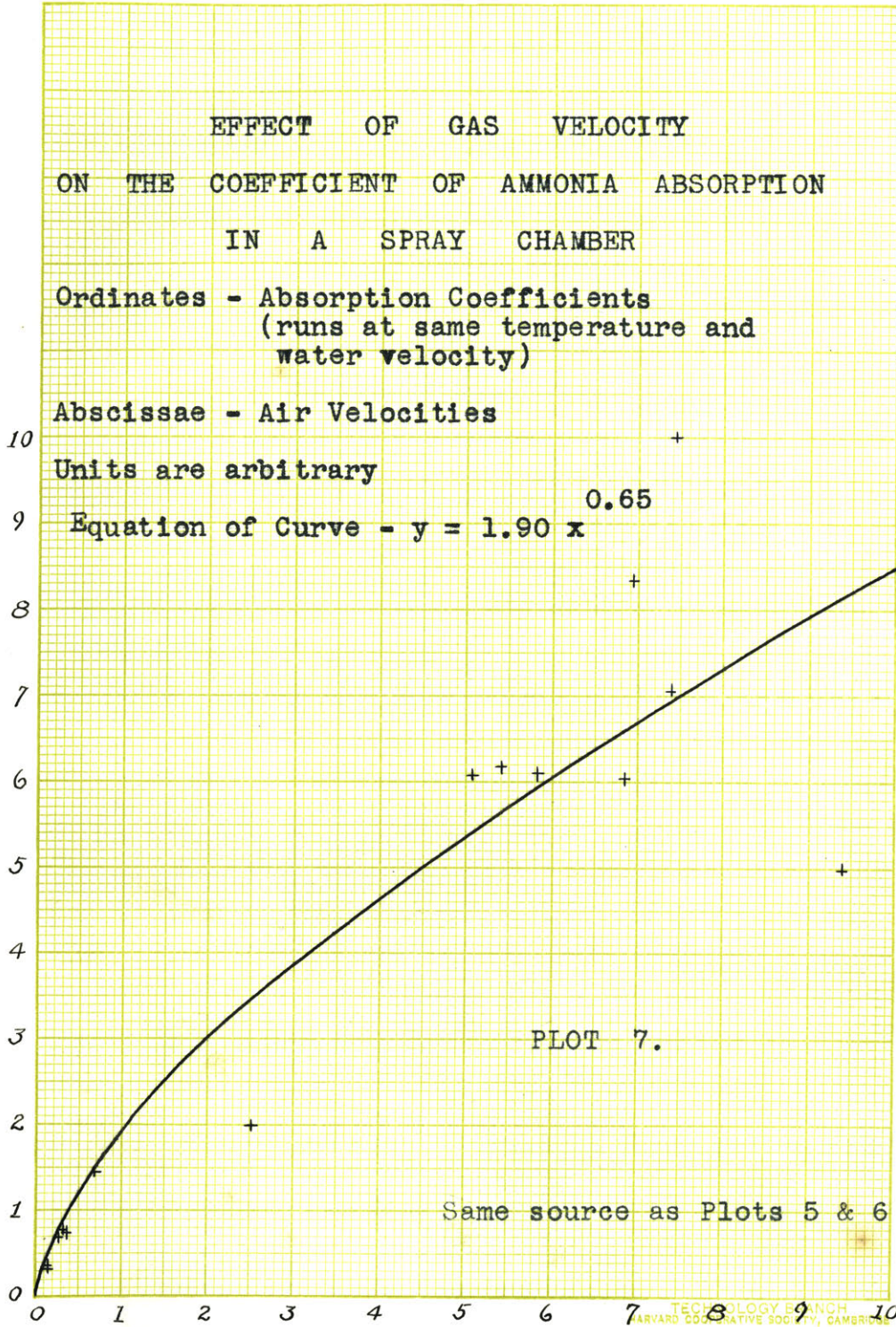PLOT 7.

Same source as Plots 5 & 6

Further unpublished data from
tests on a spray-nozzle chamber used for
dehumidification indicate that for this type
of equipment the effect of air velocity is
slight although some increase in h can be
noted as the air velocity rises.
Irregularities in the values of h caused by
other factors made it impossible to accurately
estimate a power function to be applied to the
air velocity and furthermore this latter was
not varied over a very wide range.

Spray-
Nozzle
Chamber

Farrow and Hopkinson (12) operating
a spray tower for cooling hot condensor water,
calculated h, the coefficient of heat transfer,
from the general formula

$$\frac{Q}{\theta} = h \; V \; \Delta T_{\text{average}}$$

where $\frac{Q}{\theta}$ is the sensible heat taken up by the
air per minute, T is the average temperature
difference between water and air, and V is
about 1700 cu.ft. Their water flow and
temperatures and the initial humidities of
the air were varied over a considerable range,
yet when the results were calculated by this
method h was found to be approximately constant
as 0.33 B.T.U. per minute per cu.ft. per degree
Fahrenheit.

Spray
Cooling
Tower

Very little variation in air velocity was
possible in this tower and the slight differ-
ences which did occur had no appreciable
effect on the coefficient.

In all cases studied the rate of flow
of the liquid had only a slight effect on h
and this effect could be expressed by a
hyperbolic function of the formula $h = \dfrac{CW}{W+b}$

where W is the rate of the flow of the liquid.

General
Results
of
Tests

The table given below furnishes a fair
estimate of the value of the power function
which should be applied to the gas velocity
in the formula $h = cV^n$.

Type of Equipment	Value of "n" in formula, $h = cV^n$
Coke Tower	1.5
Glass Bubbler	1.0
Slotted Bubbling Caps	0.9
Centrifugal Spray Chamber	0.65
Spray Nozzle Chamber	Very low
Spray Cooling Tower	Very low

If the operation of these different
types of equipment be considered it is seen
that the theory of the effect of gas velocity
past the walls is borne out. In the coke
tower gas velocity exerts its maximum effect
and n is high because the water is not carried
along by the gas but remains on the coke.
As a result the velocity of gas relative to
liquid increases about proportionately
to the absolute velocity of the gas, and the
effect of the latter is marked. At the other
end of the table those machines which spray
drops into the air give low powers of n.
This was predicted on page 15 because the
relative velocity of gas to liquid could
be only slightly increased by a large increase
in absolute velocity.

Comparison
of
Results
with
Theory

CONCLUSIONS

The results of many investigations have
shown that the rate of interaction between
gases and liquids can be expressed in the form

$$\frac{dQ}{d\theta} = k \; V \; (P-p)$$

where matter is being transferred, or as

$$\frac{dW}{d\theta} = h \; V \; (T-t)$$

if the transfer is one of heat. The two
coefficients, h and k, are closely related,
and for any specific equipment operating
under definite conditions the ratio $\frac{h}{k}$ should
equal s, the specific heat of the gas.

The values of h and k are affected
primarily by the design, but also by various
operating factors such as gas velocity, rate
of flow of liquid, temperature, and liquid
employed. Equipment which has a large contact
surface per unit of volume gives high values
of h or k, and vice versa.

Gas velocity affects the coefficients as a
power function which varies with the nature
of the liquid-gas contact. Where the liquid
held on a solid surface so that it is not
picked up as a spray by the gas, the effect
of gas velocity is high. In packed towers, for
example, h varies approximately as $V^{1.5}$. In
bubbling equipment this power is about unity

Gas
Velocity

and for spray design decreases to very
low values. This means that gas velocity
does not greatly affect the rate of
interaction between a gas and a spray carried
in it, since the relative velocity between
gas and liquid can be only slightly increased
by a large increase in the speed of the gas
through the apparatus.

Liquor flow has only a slight effect
on the coefficient with the rates normally   Liquor
                                                 Flow
employed. If the rate is reduced too low,
however, the exposed surface of contact is cut
down and the coefficient drops off rapidly.
The effect is best represented by a hyperbolic
function of the form

$$h = c \; \frac{w}{w + a}$$

Increasing the temperature undoubtedly
raises the coefficient, but the exact
relationship is not known sufficiently well
to permit generalization. Finally, the
nature of the liquid must greatly affect h   Other
                                                 Factors
and k, but since all experiments to date have
been made with water or aqueous solutions
nothing is quantitatively known about this
subject.

The table below gives rough
approximations of the coefficients of heat
transfer which might be expected from
various types of equipment in normal
operation. These values are calculated on
the assumption that dehumidification is
being carried out in each machine, and hence
they give an estimate on the comparative
efficacies per unit volume of the typeslisted.
h is expressed as B.T.U. per cu.ft. per minute
per degree Fahrenheit and is used in the
formula

Comparison
of
Types

$$\frac{Q}{\theta} = h \, V \, \Delta \, T$$

Type	Value of h
Packed Tower (velocity = 3 ft. per sec.)	4
Boiling Caps (3 caps per sq.ft. of plate)	1
Spray-Nozzle Chamber	1.5
Spray Cooling Tower	0.3

BIBLIOGRAPHY

1. W.K.Lewis   --   The Principles of Counter-Current
        Extraction.   Jl.Ind.& Eng.Chem.,Sept.1916.

2. W.Nusselt   --   Die Waermeuebergang in Rohrleit-
        ungen.   Verein Deutscher Ingenieure. 89,1910.

3. H.C.Weber   --   The Transfer of Heat From Gases To
        Solids.   S.B.Thesis,M.I.T.1918.

4. M.M.Beckett   --   The Flow of Heat between a Solid
        Surface and a Gas.   S.B.Thesis,M.I.T.1920.

5. W.K.Lewis   --   Notes on Drying.   Neostyled for
        Student Use at M.I.T.1920.

6. A.W.Kenney   --   A Rational Study of Counter-
        Current Extraction.   M.S.Thesis,M.I.T.1914.

7. V.A.Stewart   --   A Study of the Counter-Current
        Absorption of Gases.   S.B.Thesis,M.I.T.1915.

8. J.Keats   --   A Study of a Coke Tower as a Dehu-
        midifier.   S.B.Thesis,M.I.T.1920.

9. R.G.Mosscrop & R.J.Tobin   --   An Investigation of
        the Absorption in Soda Ash Solutions of Carbon
        Dioxide from Flue Gases.   S.B.Thesis,M.I.T.1920.

10. C.E.Carlson & J.Harrop   --   A Study of Gas
        Absorption.   S.B.Thesis,M.I.T.1920.

11. B.M.Reynolds & F.W.Sanders   --   The Absorption
        of Gases by Liquids.   M.S.Thesis,M.I.T.1920.

12. E.S.Farrow & F.J.Hopkinson   --   Experiments on a
        Spray Type Induced-Draft Cooling Tower.
        S.B.Thesis,M.I.T.1920.

13 Most recent article, by Whitman & Keats, submitted to
    Jl. Ind & Eng Chemistry in June 1921
    "The Interaction of Gases and Liquids." WGW