THE EVAPORATION OF SMALL SPHERES.

BY IRVING LANGMUIR.

THE evaporation of small spheres of iodine in quiet air has been studied by Harry W. Morse.[1]

The spheres of about one millimeter diameter were placed on the flat pan of a microbalance and weighed at intervals until they disappeared. The particles remained spherical in shape throughout the experiment.

The experiments indicated that the rate of loss of weight was accurately (within an average error of about one per cent.) proportional to the *radius* of the sphere and not to its *surface*.

This experimental fact was considered remarkable, but no theoretical explanation was suggested.

Several years ago I had occasion to make a rather detailed study of the convection of heat from small wires in air and other gases[2] and found that the heat loss by "convection" consists essentially of *conduction* through a film of relatively stationary gas around the wire. In other words, close to the surface of the wire the temperature gradient is so great that the heat carried by conduction is large compared to that carried by the motion, whereas at a greater distance the reverse is true. According to this theory the heat loss from a wire or other small body is given by the equation

$$w = s(\varphi_2 - \varphi_1), \tag{1}$$

where w is the heat loss in watts, s is the shape factor of the gas film, and $\varphi_2 - \varphi_1$ is equal to $\int_{T_1}^{T_2} k dT$ where k is the heat conductivity of the gas and T_2 and T_1 are the temperatures of the wire and the surrounding gas respectively.

This simple theory was found to agree excellently with experiment for wires of all sizes at temperatures varying from 100° up to the melting point of platinum or even that of tungsten and in several gases including air, nitrogen, argon, carbon dioxide, carbon monoxide, hydrogen and mercury vapor.

[1] Proc. Amer. Acad. Arts & Sciences, Vol. 45, April, 1910.

[2] Langmuir, PHYS. REV., *34*, 401, 1912. Proc. Amer. Inst. Elect. Eng., *31*, 1011, 1912. Trans. Amer. Electrochem. Soc., *23*, 299, 1913.

It is natural to assume that the evaporation of small objects in air should be closely related to the convection of heat from bodies of the same shape. By applying similar reasoning we are led to the equation

$$-\frac{dm}{dt} = s\int D d\rho. \tag{2}$$

Here $-dm/dt$ represents the rate of loss of weight, s is the shape factor of the relatively stationary gas film, D is the diffusion coefficient and ρ is the partial density of the vapor of the evaporating substance. For the low concentrations of vapors we are considering, D will be practically independent of ρ. From the ordinary gas laws we may place

$$\rho = \frac{pM}{RT}, \tag{3}$$

where p is the vapor pressure of the evaporating substance, M is the molecular weight, R the gas constant and T the absolute temperature.

The shape factor for a spherical shell is[1]

$$s = \frac{4\pi ab}{b - a}, \tag{4}$$

where b is the radius of the outside of the film of gas and a is the radius of the evaporating sphere. If we assume that b is very large compared to a we obtain

$$s = 4\pi a. \tag{5}$$

Substituting this together with (3) in (2) we find

$$-\frac{dm}{dt} = \frac{4\pi aDMp}{RT}. \tag{6}$$

This theory thus leads directly to the result that the rate of evaporation is proportional to the radius of the sphere.

It is of interest to calculate the value of D from Morse's experiments by means of the above equation. Morse found that

$$-\frac{dm}{dt} = ka. \tag{7}$$

The value of k can best be found from the experimental data by plotting $m^{2/3}$ against t. This gives a straight line whose slope is equal to $k/3\sqrt[3]{6/\pi\rho}$, where ρ is the density of the iodine spheres (4.95). In this way the values of k obtained by Morse are found to be

For first sphere, $k = 1.80 \times 10^{-6}$ g. per sec. per cm.

For second sphere, $k = 1.86 \times 10^{-6}$ g. per sec. per cm.

[1] See Flow of Heat through Furnace Walls. The Shape Factor, Langmuir, Trans. Amer. Electrochem. Soc., *22*, 55, 1913.

Combining (6) and (7)

$$k = \frac{4\pi DMp}{RT}. \tag{8}$$

Substituting $k = 1.83 \times 10^{-6}$; $M = 254$; $p = 271$ bars; $T = 298$; and $R = 83.1 \times 10^{6}$ we find

$$D = 0.053$$

for the diffusion coefficient of iodine vapor in air at 20° C.

Because free diffusion in all directions was hampered by the sphere resting on a flat surface it is probable that this value is somewhat too low, probably $D = 0.07$ would represent more nearly the actual diffusion coefficient.

As far as I know there are no available published data on the diffusion coefficient of iodine vapor in air, but the above value is a perfectly reasonable one when compared to other substances of high molecular weight. Thus the diffusion coefficient of carbon dioxide ($M = 44$) in air is 0.164; of acetic acid ($M = 60$) 0.122; of butyric acid ($M = 86$) 0.061; and of benzene ($M = 78$) 0.086. The iodine molecule is heavier but of smaller cross section than those of these substances, so that the diffusion coefficient 0.07 is in good agreement with the others.

These results therefore support the theory that the evaporation of the small spheres of iodine is determined simply by the rate of diffusion through the surrounding air and that no allowance needs to be made for air currents.

The results indicate also that the air in contact with the iodine surface is always saturated and that the actual rate of exchange of molecules between the solid iodine and its surrounding vapor is very rapid compared with the rate at which the vapor can diffuse away through the air.

This theory can undoubtedly be applied to evaporation from all very small objects. In the case of larger objects experimental data must be obtained as to the thickness of the film through which diffusion occurs just as has been done in the case of convection. In fact rough experiments seem to indicate that the thickness of these relatively stationary films are practically the same for diffusion phenomena as for convection.

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