THE UNDERLYING PRINCIPLES OF VENTILATION

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IT is the popular view about ventilation that the atmosphere we breathe needs to be kept "fresh", because when it becomes "foul" it contains ingredients of much danger to health. While there is very important truth in this, there is another side of the truth which has apparently not yet been realised by the public at all, and of which indeed scientific men have only in quite recent years been apprised. Everyone knows that "sudden chills" should be avoided. But the heating and cooling effects of the atmosphere have a significance which extends far beyond mere physical comfort and discomfort. They have benefits and risks for health which are not to be summed up as the warding off or incurring of "a cold". It is to explain to the general reader this quite late advance in scientific hygiene that the present article will be devoted.

The survival of living things depends essentially on their ability to adapt themselves to their environment, and their activities and well being from time to time are greatly affected by the changes which may occur in it. In the lower forms of animal life the environment consists of water in which, apart from temperature, the changes are mainly chemical in nature and the responses of the animal are associated very largely with its search for food. In the higher forms (terrestrial animals) the environment is the air and the obtaining of food now comes to depend to a lesser degree on those senses, such as taste and smell, which respond to *chemical* stimuli, and to a greater degree on others, such as vision and hearing, that respond to *physical* stimuli. At the same time the animal becomes much more sensitive towards other physical properties of its environment, especially those which affect the temperature of the body. Certain terrestrial animals have a body temperature which runs parallel with that of the atmosphere, being usually slightly above it. These are known as "cold-blooded" animals. In summer they are active in their movements and they greedily consume large quantities of food, but in winter they lie buried in mud or hidden away in protected places in a practically dormant state, with the fire of life gone out almost to a flicker, and without any food. The activities of such animals are dependent mainly upon the temperature of the atmosphere. The frog and the snake are good examples. The other group of animals, called "warm-blooded", have a body temperature which is usually considerably above that of their environment, and which is maintained at a practically constant level irrespective of changes in the latter. This constant high temperature within the body of these animals is necessary for the proper activities of the various organs and tissues; if it should rise or fall even by a few degrees from the normal, life becomes impossible. Evidently then for the maintenance of its existence the warm-blooded animal must be furnished with some mechanism by which heat is produced by its body at a rate which is equal to that at which it is lost from the surface, owing to the cooling effect of the environment. On the ability of such animals to adjust the balance between production and loss of heat in the body must depend to a large extent their well-being and, ultimately, their very existence. The adaptation of man towards the varying cooling influences of his environment is the most important aspect of the problem of ventilation. It is the purpose of the present article to explain as simply as possible how this adaptation is brought about, and then to indicate certain practical applications which should guide us in providing a suitable indoor environment.

Every part of the interior of the body is maintained at a constant temperature by the circulation of the blood. The heat is produced mainly in the muscles, and it is lost mainly from the skin, the blood being the transporting agency between the two. The muscles may therefore be regarded as the furnaces of the body to which, on the one hand, the blood transports the fuel which it absorbs as food stuffs from the alimentary canal, and from which, on the other, it carries away the heat to the fine network of minute blood vessels which underlies the skin. The heat is produced in the muscles by essentially the same chemical process as if the food-stuffs had been burned outside the body,-viz. by oxidation—and the heat which is set free is quantitatively the same in both places. The fine film into which the blood is spread out in the vessels of the skin and in the lungs exposes it to the cooling influence of the atmosphere. By the physical processes of radiation, convection and to a lesser degree of conduction much of the heat is lost and the cooled blood returns to the muscles to be warmed up again. The temperature of the interior of the body is therefore the result of a balance between heat production and heat loss. If the loss of heat becomes changed in either direction, then heat-production must become reciprocally altered and the whole well-being of the animal, dependent as it is on a constant body temperature, must depend on the precision and promptitude with which the adjustment can be made. By way of illustration, let us suppose that the body is exposed to an atmosphere of diminishing cooling power as, for example, in a hot stuffy room. The first thing that happens is that the blood-vessels of the skin become dilated, and soon it is observed that the skin becomes flushed with blood. But this drafting of blood to the surface may not sufficiently cool the blood, so that other mechanisms have to be called into play. These are increased breathing and sweating. By the former of these more air enters the lungs, and so absorbs more heat from the blood contained in the fine mesh-work of vessels which is spread on the walls of the minute air-sacs in which the air-tubes terminate. The heat in this case is used only to a small degree for the purpose of warming the inspired air, but mainly because it is required to vaporise water so as to make the expired air fully saturated with moisture at the temperature of the body. This process of vaporization of water absorbs very large quantities of heat, and it need scarcely be pointed out that it is the one upon which depends the other mechanism mentioned above, namely, the cooling influence of sweat. It is probably only after these three cooling mechanisms,-greater blood flow in the skin, quicker breathing, and increased sweating—have been called into play that the body furnaces become damped down.

So intricate a mechanism to maintain the temperature of the body at a constant level must obviously depend on some controlling agency. This consists of a nerve centre, situated somewhere in the base of the brain, which transmits impulses that exercise control over the freedom of blood supply of the skin, the rate of breathing, and the activities of the sweat glands. This "thermogenic centre", as it is called, does not influence these functions directly, but only indirectly, by acting on the lower nerve centres that have been set apart, one for each of them. By such an arrangement their activities may accordingly be altered, each through its centre, for purposes other than the control of heat loss. For example, the skin may become flushed, not in order to increase the cooling of the blood, but because of some local irritation of the skin, or because of emotions. The thermogenic centre is, as it were, a Higher Command entrusted with the adjustment of the body temperature through its power to direct the activities of various lower centres, which may, however, be called into play for other purposes.

In order that the thermogenic centre may properly direct the lower centres, it is necessary that it be informed not only of the existing body temperature but also of the present state of the various cooling mechanisms. It is no doubt exquisitely sensitive to any change in blood temperature—a most delicate thermostat—but it is more than this, for it is also the recipient of nervous impulses carried to it in the nerves coming from the skin, and these impulses are set up by changes in the cooling influence of the environment. This necessitates that the skin should be provided with special organs sensitive to changes in temperature, and it is probable that these are the so-called "hot and cold spots" the presence of which can be readily demonstrated by drawing the point of a lead pencil over the back of the hand. In certain places the pencil feels cold; in others, warm. It is not the actual temperature of the air that affects these sensory organs, but its cooling effect; that is, its power of causing heat to leave the body. This means that it must be *the fall of temperature from the deeper to the more superficial layers of the skin that acts as the stimulus*, and it is interesting to note that this fall may be very considerable when the cooling power of the atmosphere is great. In anaesthetised rabbits we have placed several delicate thermocouples, mounted in hypodermic needles, at varying depths of the skin and subcutaneous tissues, and have observed that whereas there may be little difference in temperature between these two regions when the skin is covered with fur, this becomes quite marked (6—8°C) when the skin is exposed to the atmosphere, as by clipping the fur. If, therefore, the cooling power of the air should become less, the rate of fall of temperature through the skin would decrease, the temperature sense organs become less excited and, as a result, nerve impulses be transmitted to the thermogenic and thence to the lower centres that control the cutaneous blood vessels, so as to dilate them and therefore cause the blood to flow more freely to the surface. The extreme delicacy of these reflexes can be well shown by placing one hand in an apparatus, called a calorimeter, by which the rate of heat-loss from the blood flowing through it may be measured with extreme accuracy, and then, when this has become steady, placing the opposite hand—or one of the feet—in cold water, when a prompt and striking diminution in heat-loss will be observed to occur! Even a draught of cold air playing on the arm or shoulder will have this effect.

If the readjustment of cutaneous blood flow does not cool the blood sufficiently, then sweating and increased breathing are excited, but there is some reason for believing that this occurs only when an actual rise in blood temperature has occurred.

But what, the reader may ask, has the control of body temperature to do with the problem of ventilation? Is not this related to the *chemical purity* of the air rather than to its cooling powers? On the contrary, it has been abundantly shown that great changes can occur in the composition of the air (i. e. increase in carbonic acid and decrease in oxygen) without any of the results supposed to occur in ill-ventilated places; on the other hand, these immediately appear when there is any interference with the cooling power of the air. It would take us beyond the scope of this article to give all the proofs upon which this—to many, I have no doubt, rather startling—assertion depends. An experiment performed by Leonard Hill may be sufficient. It consisted in crowding as many young men as possible into an air-tight cabinet provided with an observation window and an electric fan. No discomfort was felt for some time, but after 44 minutes when the dry-bulb thermometer stood at 87'F., and the wet-bulb at 83'F.,

> The discomfort felt was great; all were wet with sweat and the skin of all was flushed. The talking and laughing of the occupants had gradually become less and then ceased. On putting on the electric fans and whirling the air in the chamber the relief was immediate and very great, although the carbon dioxide had risen to 5.26 per cent and the oxygen had fallen to 15.1 per cent, and this in spite of the temperature of the chamber continuing to rise. On putting off the fans the discomfort returned. The occupants cried out for the fans. No headache or after effects have followed this type of experiment which has been repeated five times.

Surely nothing could be more convincing, but if further evidence is demanded, it may be found in the observation that when a person *outside* the chamber breathed through a gas-mask connected by wide-bore tubing within the chamber, no symptoms of discomfort developed, at the time when the persons inside were entirely overcome, or, again that although one of the persons inside was allowed to breathe pure outside air (also through a mask) he suffered the same symptoms as the others.

No doubt in extreme conditions, such for example as existed in the famous Black Hole of Calcutta, the oxygen of the air may fall so low and the carbon dioxide rise so high that symptoms result, but these are not the symptoms that are ordinarily caused by faulty ventilation in every day experience. They are acute symptoms of much greater immediate danger to life.

Ventilation, then, is a problem of the cooling influence of the atmosphere on the body. Out-of-doors this cooling influence is usually quite different from what it is indoors, even although the temperature may be the same. It differs in two particulars, namely; it is greater on an average, and it varies much more from moment to moment out-of-doors than indoors. Let us see, then, upon what the cooling power depends, for it is plain that if we understand this we shall be in a position intelligently to regulate the ventilation indoors. The cooling power depends on three physical properties of the atmosphere: its temperature, its relative humidity, and its movement. It is the usual practice to measure the average temperature of a room by means of an ordinary (dry bulb) thermometer, but the information thus acquired is of little significance, since the temperature we measure is only that of the board on which the thermometer is mounted; it is only the actual temperature which has become established on an object exposed in one part of the room. To be of any real value, therefore, the record of these temperatures should be taken at various places. Even with this precaution however, the readings are not of very much value, for although the cooling influence of the air will be proportional, roughly, to the difference between its temperature and that of the body, the low conductivity of air greatly diminishes its cooling effect. The second property, humidity, owes its cooling influence mainly to the fact that the rate of evaporation of moisture from the surface of the body depends on the extent to which the air is already saturated. When the temperature is low the air can take up as vapour only small quantities of moisture, and, as we have already seen, there is little tendency to sweating. At the same time, however, such air feels much cooler than dry air at the same temperature. This fact is familiar to all who have had opportunity to compare dry and moist climates in winter. The cooling sensation of air of high humidity is usually ascribed to its greater heat-conducting power, but it should be remembered that it is not so much because the wet air itself conducts heat better, but because it greatly diminishes the heat-insulating properties of the clothing.

On the other hand, when the temperature is high (above 67′F) sweating is likely to become an important factor in the cooling of the body, and the rate of evaporation of the sweat depends of course on the extent to which the air can take up more moisture before it becomes saturated. This relative humidity, as it is called, is measured indirectly by reading the wet bulb thermometer. In this instrument the bulb is covered by a cloth kept constantly soaked with water. The water evaporates into the air and cools down the thermometer, so that the height at which the mercury stands depends on the rate of evaporation and therefore on the relative humidity. The difference between the wet bulb and the dry bulb readings can be converted into terms of the relative humidity by use of a formula, but to do this is of comparatively little practical value.

The third and last property—the actual cooling power—is by far the most important, but unfortunately it is also by far the most difficult to measure. Its value depends partly on the temperature and humidity, but also on the movement of the air. It is therefore much more inclusive than the other values. It is the whole, whereas these are only parts. Its importance in determining the comfort of man has already been shown in the experiment with the respiratory cabinet where the turning on of a fan removed the discomfort, although no change occurred in the temperature or humidity. Various instruments have been devised to measure the cooling power. The most successful of these, so far, is the kata-thermometer of L. Hill, in which the time required for an alcohol thermometer to cool through a certain range of temperature is measured. Since, as we have seen, the cooling power will depend partly on the difference of temperature between the body and the air, the thermometer is first of all warmed in water to a little above the temperature of the body; it is then removed, and, after drying, held in the air. The level of the alcohol in the stem is then observed, and the number of seconds required for it to fall from, say, 100° to 95°F. is measured, preferably by means of a stop watch. The greater the cooling effect, the more rapid the fall, and the result may be expressed in actual units of heat loss (calories) by division of the seconds by a factor which is written on the stem of the instrument. When used in this way the rate of cooling of the instrument is independent of the relative humidity of the air, and to include this influence it is usual also to employ a kata-thermometer with its bulb covered by a moist cloth. The kata-thermometer is, however, not very adaptable to general use, because the measurements by it take some time and skill. Simpler instruments based on the same principle are therefore being experimented with, and it is quite likely that it will very soon be possible to construct one which will be as simple to read as an ordinary thermometer.

Leonard Hill and his collaborators have collected numerous observations by the dry and wet kata-thermometer under all varieties of atmospheric conditions both indoors and out-of-doors. A most significant difference between the cooling influences in the two places has come to light, namely, that there are great variations in the cooling power within short periods of time out-of-doors, whereas indoors the readings are likely to be fairly stationary even when the temperature and humidity in the two places are not the same. This would indicate that the thing we should aim at in a well-ventilated room is *variety* in the cooling power of the air. Monotony in this respect is evidently not in the interests of a sense of well-being. Frequent change of air all over the room or hall, without setting up uncomfortable draughts, is the aim of good ventilation, and there can be no doubt that this is most satisfactorily accomplished in large places by the proper use of fans and in dwelling rooms by open fire-places, or, where this is not feasible, by having the windows slightly open.

We cannot however venture here into the field of the practical methods of ventilation. Suffice it to say that if the principles upon which this depends are thoroughly appreciated it is usually not difficult, in small places at least, to devise some means by which the air can be kept in constant motion. To ensure this in large meeting places is the problem of the ventilating engineer.