Civil and Mechanical Engineering.

ON THE CIRCULATION OF WATER IN STEAM BOILERS.

ADDRESS BEFORE THE

AMERICAN RAILWAY MASTER MECHANICS' ASSOCIATION,

at their Meeting in Philadelphia, June, 1876.

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MR. PRESIDENT AND GENTLEMEN:—I am much gratified by the honor conferred upon me in being requested to address you upon the subject of the phenomena attending the ebullition of water, and with the risk that I may be reciting facts well known to all, and certainty that what I shall say will be merely elementary, I venture to quote a portion of a lecture delivered by me before the Franklin Institute, trusting that a new view of old facts may not be out of place.

The three forms of matter—solid, liquid and gaseous—are incident to some definite quantity of heat which accompanies each form, which is known as the latent heat, and varies in amount for the different substances. For water, which is the substance under consideration at this time, the latent heat added to and absorbed in the change of form from ice at 32° to water at the same temperature, is $142^{\circ}\cdot65$ (Person), and in the change of form from water to steam of 32° is $1,092^{\circ}$ (Regnault). But the sensible temperature of a liquid at which it will vaporize is found to vary with the pressure (or tension) of the vapor above it, and the tension of steam at 32° is only $0\cdot085$ lbs. per square inch, while the pressure of the atmosphere is $14\cdot7$ lbs. per square inch. Ebullition or free boiling of water does not take place under atmospheric pressure until the water is heated up to 212° , at which point the tension of steam is equal to the usual atmospheric pressure of $14\cdot7$ lbs. per square inch, and the latent heat of change of form from water at 212° to steam at the same temperature, is 966° (Regnault).

The other properties of water, as regards heat, with which we have to do in considering the circulation in a boiler, are its expan-

sion and its rate of conductivity. Water expands (on being heated) at anomalous rates: about 0·8 per cent. from 40° to 100°, about 3·9 per cent. from 40° to 200°, about 8·7 per cent. from 40° to 300° and about 11·5 per cent. from 40° to 350°. The conductivity of water is exceedingly slow (as it is in all liquids when not in motion), so slow that it can be assumed to be absolutely non-conducting in the present inquiry. As a consequence of this non-conductivity of water, it can only be heated by the application of heat below, and by transfer and diffusion of the state of heat by means of the motion of the particles of the fluid mass; and uniformity of temperature is attained in such a mass only by continual circulation.

The usual and accepted method of heating water, therefore, is by placing it in a vessel, to the under side of which, heat is applied, which heat is transferred through the material of the vessel and imparted to the water. The film of water in contact with the inner surface of the vessel, at the place where its outer surface is exposed to the fire, becomes heated and expands and mixes with the water immediately near it, until a stratum of water is formed which is lighter than the mass of water above it and tends to float, and its flow being supplied instantly by heavier water, a circulation is commenced. After the establishment of a circulation of slow velocity, acceleration goes on, until at some rate of movement, the friction of the currents of water against the sides of the vessel or against themselves (for eddies, whirlpools and cross-currents will form in a vessel under such circumstances) offers a resistance to greater velocity, exactly equal in amount to the disturbing force of the expanded water in trying to rise. The slow run of first movement with gradual increase of velocity and circulation, arises from the fact that particles of water are, in common with those of other bodies, either solid, liquid or gaseous, subject to the laws of the application of force; whereby they do not commence to move until some resistance is overcome, nor do they cease to move until the acquired momentum is compensated. So long as the heat imparted to the water is below the boiling point, a circulation of hot water can be urged with perfect quietness in properly formed vessels, and in tubes, until an equilibrium of temperature of the water in the vessel, or tube, is established; and when the heat of the water is abstracted in the course of circulation, a high velocity of current can be attained, and great quantities of heat can be transferred without disturbance of flow.

But as the boiling point approaches, another train of conditions is brought to bear, which may be better considered by referring to the accompanying figure.

Fig. 1.

Fig. 2.

one pound per square inch. The relations of pressures and of temperatures of ebullition, in this column of water are: at the surface there will be the pressure of the atmosphere = 14.7 lbs., with its corresponding temperature of ebullition = 212°; at the depth of 1.2 feet the pressure will be 15.2 lbs., and the temperature of ebullition = 213°·65; and at the bottom, at the depth of 2.4 feet, the pressure will be 15.7 lbs., and the temperature of ebullition 215°·3.

The effect of the application of fire to the bottom of this vessel having first been admitted to raise the temperature of the entire mass of water to 212°, and having expelled most of the air which was absorbed in the water at its normal temperature before heating, will next be extended to the formation of steam as the means of dispersing the constant addition of heat; and somewhere in the height of the column, a point will be reached where the rate of circulation will permit the return water from the top surface, which will inevitably have the temperature of 212°, to reach the bottom where it will be heated, let us say, to 213°·65 by the fire.

The specific heat of water compared to that of iron is very great (about nine times as great), and a film of water of the same thickness as a sheet of iron, with which it may be in contact, has a little the greater capacity for heat; but the rapidity of convection of heat in water is far greater than that of the conduction in iron, so the general temperature of the water in contact with the iron is maintained with the smallest excess of temperature of the iron.

Fig. 1 represents a vessel containing water exposed to the action of a fire upon or under the bottom of a vessel. It is supposed that the depth of water in the vessel is 2.4 feet, when it would follow, as the weight of a cubic foot of water at 212° is very nearly 60 lbs., that the pressure of the column of water at the bottom of the vessel is very nearly

The extreme tenuity of the gases of combustion, although they have about twice the specific heat of the iron by weight, reduces the relative quantity of heat, by volume, in contact with the bottom of the boiler to such an extent that the external temperature of the iron where exposed to the fire, may, for ordinary practice, be taken as that of the water within the boiler. Still, notwithstanding the great rapidity of convection, the first result from the intense heat of a flame is to create numerous exceedingly small vesicles of steam (represented by dots on Fig. 1) in contact with the internal surface, which float away from it, and in a short distance are absorbed into the water again, giving out their heat to the water of lower temperature. With active firing these small vesicles will form a turbid cloud, and the closing up of the vesicles, and contact of water with the bottom, will produce a characteristic singing noise which attends boiling, and is particularly noticeable just before the boiling point is reached, when the water at the bottom may be a little above 212° , while that of the mass above may not have attained that temperature. In the case which has been supposed, where the temperature of the ascending current is to be $213^{\circ} \cdot 65$, after this cloud of vesicles is absorbed, which will occur within two or three inches of the bottom, the water will become solid again, and rise to the height of 1·2 feet before the pressure upon it will have become sufficiently reduced to allow a bubble of steam to form.

At this height evaporation should commence ; it will, however, not do so, because the heat is completely disseminated in the water, and because water has considerable adhesive force or strength of itself (although the particles move upon or slide over each other with much ease, they offer a positive resistance to being separated, which, by the laws of thermodynamics, is measured by the latent heat absorbed), and the water will hold together even when agitated by currents and eddies, as shown in Fig. 1, until relieved of 1 to 2-10ths of a foot more of column pressure ; it then begins to exhibit, first a turbidity of small vesicles of steam intermingled with the water, which, ascending with the current and agitated together, will, by joining, form small bubbles of steam. These bubbles will have their internal atmosphere of steam, and their internal surfaces are free to give out steam to this little atmosphere, and these little bubbles, which began to form under about 15 lbs. pressure, will augment in size as the pressure is relieved, at the same time that they are grow-

ing from the formation of steam from the water surrounding them until this formation of steam will have reduced the temperature of the surrounding water to 212° , when the bubbles, and the water enclosing them, will have reached the surface.

Thus, while the circulation was produced by the levity of the column (the heated water), it is greatly promoted and accelerated by the presence of steam in bubbles in the heated mass, and the value of this agency of bubbles can be estimated as follows: A pound of water at 212° is very nearly 28.8 cubic inches or 1.60th of a cubic foot, while a pound of steam at the same temperature is 26.36 cubic feet in volume, or 1,580 times as large as the water from which it was made. The case supposed in Fig. 1 gives $1^{\circ}.65$ of heat as being expended in making steam from what was solid water at the depth of 1.2 feet of $213^{\circ}.65$ temperature. The latent heat of steam at 212° is 966° , and consequently the $1^{\circ}.65$ will make (when applied to a pound of water) 1.580th of a pound of steam, the volume of which will be 26.36-580ths of a cubic foot, or 1,580-580ths = 2.7 times the volume of a pound of water; and the mixed volume of bubbles of steam and water which will come to the surface at the temperature of 212° will be very nearly 3.7 times as great as the volume of water which was solid at $213^{\circ}.65$, lower down in the vessel, and the entire volume of mixed steam and water, above the point of the first formation of steam, will be 2.35 times that of the original water at $213^{\circ}.65$.

Perhaps it may be well to exhibit some rate of evaporation in conjunction with the supposed ebullition, and this can be done by comparison with the ordinary rate of firing of a stationary boiler, which is from 10 to 12 lbs. of coal per square foot of grate per hour, and as each pound of imperfectly consumed coal, on such a grate, yields 9,000 to 10,000 units of heat only, the total efficiency of a square foot of grate becomes 100,000 to 108,000 units of heat per hour, equal to about 30 units per second. If it be assumed that the surface of evaporation be equal to that of the grate, and that either equals one square foot, the volume of steam which will be evolved per second will be 0.8 cubic foot, whence 1.1975th of a pound of water must be converted to steam each second for each square foot of grate, or of surface of evaporation, or, in terms of the volume of water, 0.9 cubic inch of water will be evaporated to steam, and 8.27 of a cubic foot (532 cubic inches) of water will be circulated and part with its

heat each second. Thus it is evident that while the motive power to promote circulation is very great; the usual conditions of a boiler, with a restricted area of surface for evaporation, demand intense activity of circulation. (An example of higher temperature than 212° will be considered further on.)

While this current of steam and water is ascending, a corresponding quantity of water which has lost its heat must descend, and unless provision is made to separate these currents, the conflict will add to the disturbances occasioned by the formation of bubbles. In a vessel or a boiler of considerable dimensions of width as compared with its depth, the conflict will take care of itself, and the velocity of circulation, induced from the expansion of volumes of the heated and partially evaporated mass, will establish a *regime* or equilibrium of action, in the transfer of heat from the fire surface on the one hand, and to the formation of steam on the other; and the steam bubbles will appear at that point in the column of water where the equilibrium may require them as agents for acceleration. If the water surface at the top of the vessel be not large enough (a not very unfrequent occurrence) for the steam to evolve itself in the course of a quiet circulation and surface evaporation; or for the bubble below the surface to develop in size without interfering with the return circulation from the top, it will then be found that a secondary circulation, under pressure from a column of foam, will have been established (Fig. 2), and the supply of return water for the bottom will be derived from below the evaporating surface. The heated return water thus supplied will be again heated at the fire surface to a point higher than before, and the point of elevation where bubbles begin to form will be depressed, to correspond to the elevation of temperature. The bubbles will then develop and approach the surface laden with steam of higher temperature than would be sufficient to preserve a more quiet circulation, and will escape from the surface with some violence; of course a condensation into the disturbed particles of water will ensue, and the result will be the establishment of a strata of foam on the top of the legitimate circulation, and the passing off with the steam of a large quantity of water in the form of mist. This action can go on increasing in violence (with the intensity or extent of surface of the fire as compared to the volume or depth of water to which the fire is applied, taking into account the means of circulation provided) until the return water comes back to the

point of application of heat—the fire surface—at such a temperature, that the amount of heat, there supplied, will generate a bubble of steam at once; when, at this moment, the circulation is interrupted by the tendency of such a bubble to rise within the return current; the next effort of the steam is to eject the mass of water within the vessel convulsively.

Fig. 3.

Fig. 4.

This phenomena is that of the Geyser (Figs. 3 and 4). In this natural exhibition of a defective water circulation in a heated vessel, the sides of the Geyser tube or vessel are heated as well as the bottom—a condition incident to various steam boilers—and the vessel has a funnel shape, which is not so usual in boiler construction. In the normal state of a Geyser, or a mass of water in the small end of a natural funnel, is in active ebullition from volcanic heat at the bottom, (the

constant supply of water being maintained by the dripping of springs in the upper part of the cone quite near the earth's surface); and at or near the time of an eruption, the boiling water is in, or close upon, an equilibrium of circulation and ebullition. By throwing sods, or substances of about the same specific gravity with the water, down the hole, the circulation is impeded, and a quantity of steam of greater pressure than what is due to the column of water is formed, until the mass of water is lifted from the bottom, and the bubble of steam thus evolved at the bottom will augment from the water surrounding it, especially as the piston of water above it, gains in diameter and diminishes in thickness (as the funnel increases in size) *thus reducing the pressure upon the inclosed steam.* The heat of the bottom and walls of the tube will expand the volume of inclosed steam, and evaporate with great celerity the spray or such small quantities of water as may trickle down, and the two causes will preserve the pressure of the steam, beneath the water, to the point necessary for the production of the phenomena, notwithstanding the increase of volume. An eruption of much violence will follow—the whole column of water being expelled with great force, accompanied by the evolvment of steam from the mass of water in the air above.

After the ejection, the fountain of water will have given out a large part of its heat; and if the time of exposure to the air were long enough, the temperature of the ball and spray would fall below 212° , while the Geyser tube would have been entirely relieved from pressure by the expansion and escape of the inclosed steam, so that the mass could fall back into the heated chasm. But not only will scarcely time enough have passed for the water to have divested itself of heat, but the mass which falls will be a broken shower of intermingled steam, air and water; and also the internal surfaces of the tube will have attained, from the absence of water in contact with them, a very high heat, which will be given out to the first small quantities of water which return, generating a large volume of steam, without loss of heat in heating water; and several successive discharges will occur before such degree of quietness is reached, as will allow the water to remain within the funnel; and even after this, much turbulence will be exhibited before the regime of circulation will produce a stable condition of movement.

In my examples, Figs. 1 and 2, the phenomena of ebullition have been shown at the atmospheric pressure, and although it is not intended at this time to carry this discussion beyond the mere elementary exhibitions, yet it may be well to make a similar sketch and computation at higher temperatures.

Fig 5

Fig. 5 represents a vessel containing water exposed to the action of heat similar to those shown in Figs. 1 and 2 (*ante*), except that a permanent pressure of 120 pounds per square inch above the atmosphere is maintained, under which the generation of steam is supposed to be going on. In consequence of the expansion of water at higher temperature, the height of column which represents one pound pressure now becomes 2.54 feet (in place of 2.4 feet), and in consequence of the properties of steam, the difference of temperature corresponding to one-half a pound pressure per square inch becomes $0^{\circ}\cdot3$ (in place of $1^{\circ}\cdot65$). The other figures change as follows: The latent heat at $349^{\circ}\cdot7$ becomes $= 870^{\circ}$ (in place of at $212^{\circ} = 966^{\circ}$). A pound

of water has a volume of 30.9 cubic inches (in place of 28.8); a pound of steam has a volume of 3.3 cubic feet (in place of 26.36). The volume of steam as compared to the water from which it is formed at $349^{\circ}.7$ is as 185 to 1 (in place of at 212° as 1,580 to 1). The mixed volume of steam and water at the surface will be but 1.06 times that of the solid water at 1.27 feet below, while the total column of mixed steam and water above the solid water is 1.03 times that of the solid water in this case (in place of 2.35 times at atmospheric pressure). It will be seen from this that the tendency to foam, falls off rapidly as the pressure at which evaporation is permitted, increases—when the bubbles cease to be so large an obstacle to the return circulation; and also that the motive power for circulation gained by the levity of the steam bubbles, falls off with increase of pressure. The manifest effect of this deficiency in inducing circulation, will be to move the point at which the bubbles will begin to form nearer to the fire surface (lower down in the vessel), and to *define the dimensions* of the streams of rising and returning currents. If the rising current is small enough, the bubble of steam may begin to form on the very bottom of the vessel, rise up enlarging in magnitude to the surface, enveloped all the while in a column of water of (in this supposed case) $350^{\circ}.3$ temperature at the bottom—enlarging by relief of pressure, which acts in two ways; first, by permitting expansion, and second, by causing evaporation into its (the bubble's) atmosphere, and finally, the bubble of steam is evolved at the top, quietly at $349^{\circ}.7$.

Fig. 6.

There are two other phenomena of boiling which should be stated here. The first of these is to a great degree experimental. If water is carefully heated in a nicely-formed vessel, Fig. 6, [first taking the precaution to boil it, so as to expel the air which all water absorbs into its volume in quantities relative to the temperature (diminishing with their increase)], applying the heat so as to preclude any disturbance in the course of circulation, the temperature can be elevated much beyond the boiling point without the commencement of ebullition. Mr. Knight, the Secretary of the Franklin Institute, has succeeded in reaching a temperature of 247° in an open vessel, which indicates an internal tension for the water of about 14 lbs. per square inch. Of course the commencement of evaporation under these, cir-

circumstances is a convulsive ebullition. The presence of a little broken glass or of particles of any material of splintery form, will prevent the phenomena; and the introduction of any sharp object will almost certainly incite ebullition whenever the boiling point is exceeded.

This peculiar property of heated water seems to be the equilibrium of cohesion (before referred to), which is here manifested to the extreme of instability. The conditions by which it can be displayed are so limited that they cannot be regarded as having a possible existence in any steam boiler, in which there is not the least probability of elevation of the temperature of the water above the boiling point (at any given pressure) by securing that quiescence which all experiments have shown to be demanded for the production of this result.

The second phenomena bears a more important relation to the steam boiler. It has already been shown that water will leave a heated surface, so soon as the temperature of the entire mass has reached that degree where the increment of heat imparted at the surface, upon which it should be brought in contact, will elevate the temperature above the boiling point properly due to the pressure from the mass; and it remains to be stated how a similar repulsion can exist without the temperature of the repelled mass of water being elevated in like degree. If we suppose a heated surface, so hot and so well supplied with heat, that its *radiant heat* will generate steam, from the under surface of a mass of water, of greater tension than the subsisting pressure of the atmosphere or inclosure, together with the pressure proceeding from the weight of the mass, the mass itself will be repelled from the heated surface, and will float upon the vapor emitted. The familiar example is a drop of water upon a flat-iron; the philosophical

Fig. 7.

one is that represented by Fig. 7 and is known as an exhibition of the *spheroidal* condition of water. Water supported in this way must be evidently in very unstable equilibrium, and with the slightest inclination of the heated surface would roll on its vapor to the lowest point, and a capsule or saucer-shaped vessel is therefore indispensable to retain it.

In the course of the experiment very little heat is imparted to the ball of water, the radiant heat being spent mainly upon the under surface, while that which passes through this surface shines through the water as light shines through glass; thus, only the film, so to speak, of the under surface is heated, and much if not most of this heat upon

the surface is at once expended in generation of steam. The little heat that is imparted to the water at the under surface, in place of establishing a circulation of water within the ball, simply disturbs the centre of gravity, and induces the whole mass to roll over and allow its heavier (colder) side to find its equilibrium at the bottom; and in the operation, under the conditions stated, a spheroidal shape is assumed by the body of water.

Investigations have shown that when the surface of the vessel is heated to about 380° Fah. a spheroid of water of about two inches of thickness will be repelled and constantly supported, while the temperature of the water (with the air in a summer-hygrometric condition?) will be about 206°, or 6° below the boiling point (Boutigny).

This recital of what constitutes the spheroidal condition (so-called) of water has been made, with so much explicitness, in order to render it apparent that it is merely a simple consequence to the laws of transmission of heat from a surface to water, and not an occult property in any sense. The statement of importance in boiler construction is, that at some temperature a heated surface will repel water, and that once repelled the surface will cease to impart as much heat as before, and the repelled mass of water can become of much lower temperature than it must have had if the contact had been preserved, and these truths apply to water under pressure (atmospheric or other), and to any height of column of water upon or above the heated surface, a relative temperature being accepted for the various conditions.

Whenever the water has been once repelled from a fire surface or plate, the temperature of that surface will increase with great rapidity, and the limit of this temperature of a plate it is difficult to fix. It is certain that where there are gaseous bodies on either side of a plate, the temperature of which bodies are known, the temperature of the plate itself will be a function of the capacity for heat of the two gaseous bodies in opposite contact; but even this complex law for obtaining the heat of a plate from which water has been repelled fails in the case of the fire-box of a boiler, where half the heat from the flame is radiant heat which is absorbed into the plates of the fire-box at an unknown temperature of intensity, although the quantity of heat may be well established. But I think it safe to assert that in less than one minute's time the temperature of a 5-16 inch plate in a fire box from which water has been repelled, will become over 1,000°

Fah., and the plate will be materially reduced in strength to withstand the internal pressure.

I have not attempted to complete this application of principles to the locomotive boiler; in fact, I feel the deficiency of my elementary remarks in their want of comprehensive statement of circulation, where the return takes place from the back instead of downwards, as I have discussed; but I present these considerations as showing the direction of inquiry to be followed in the attempt to account for failures of fire-box sheets or of tubes, whenever the evidence of overheating presents itself. In such cases, I have little question that obstructed circulation and inadequate water-space have more to do with accidents than the quality or nature of the material of the plates. . . .

Mr. Briggs quoted an instance of the failure of some tubes in a class of locomotives constructed ten or twelve years since, for the Illinois Central Railroad. In this case, a cluster of seven 2-inch tubes, which were located about one foot down, upon the tube sheet, in its middle, in several engines of the same class, collapsed about one to two feet in front of the sheet. A sample of one of the collapsed tubes, which was furnished the speaker by Mr. Hayes of the Illinois Central Railroad at the time, showed a cup-shape introversion without rupture of about six inches in length, the upper side of the tube having been depressed into the lower one completely. Of course the tube had been above red heat when this occurred. The remedy was understood to have been the removal of one or two vertical rows of tubes to allow the water to circulate.

Notes on Ventilation.—Some experiments made recently by Theron Skeel, C.E., and Mr. Carl. W. Nason, at Doct. Hall's church, New York City, have given the following resulting performances of a ventilating fan :

	Number of Experiment.	
	I.	II.
Revolutions of fan per minute	66·7	110·
Difference of atmospheric pressure between inlet and outlet chambers, in inches of water	0·145	0·400
Velocity of air in duct beyond the fan, in feet per minute, as indicated by an anemometer	484	750
Cubic feet delivered per minute	9900	15370