NOTES ON THE THEORY OF THE STEAM ENGINE

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Trieste

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ON THE

THEORY OF THE STEAM ENGINE:

BEING PART OF

A Course of Instruction in the Subject

GIVEN IN

THE ROYAL SCHOOL OF NAVAL ARCHITECTURE
AND MARINE ENGINEERING.

BY

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INTRODUCTION.

The mechanical theory of heat has now for some years attained a well-established position, while its consequences are so important in the theory of heat engines, that (if true) no theory not based on it could be accepted, even provisionally, as the subject of a course of instruction in the theory of the steam engine. No doubt many numerical results are but slightly altered by the adoption of the true theory of heat, but the whole conception of the mode of operation of a heat engine is altered, and more especially we perceive with clearness, by aid of this theory, the conditions of maximum efficiency, and consequently the means whereby maximum efficiency may be attained. And for this is necessary, not merely a knowledge of the principle of the convertibility of heat and work in which the mechanical theory of heat is too often supposed alone to consist, but also a knowledge of certain other parts of that theory, not less important, though unfortunately much more difficult to understand and apply. Accordingly, the sole English work on the steam engine which is founded on the true theory of heat, namely, Professor Rankine's well-known treatise on the "Steam Engine and other Prime Movers," has always been employed as the text-book of the theory of the steam engine, in the Royal School of Naval Architecture and Marine Engineering.

As may well be supposed, however, a systematic course of oral instruction has been found necessary, on account of the very difficult form in which many parts of the subject are presented in the work in question. But the inconvenience to students and instructor of too great a dependence on oral instruction is so serious, that it was determined to draw up notes in which that part of the instruction, in which the difficulty had been specially felt, might be presented in a definite form.

We have been led to publish these notes, with some additions, from the idea that they might prove useful to persons who, although well acquainted with the steam engine and with the principle of the convertibility of heat and work, may have been deterred from a further consideration of the subject by the difficult manner in which the mechanical theory of heat is treated, not only in Rankine's work, but in almost every other work, English or foreign, with which we are acquainted. We have dwelt, therefore, exclusively on points *peculiar* to the modern theory of the steam engine, omitting all others, though of equal importance; for to consider every point would be to write a complete treatise, a work of no small magnitude, which we have no leisure to undertake. It will be found, however, that no such point of much importance is left unnoticed, unless it be fully explained in Rankine's work. Sometimes a point is noticed for the sake of readers who may have at hand no other treatise on the steam engine but Rankine's. We are far from pretending to have removed all difficulties,—the nature of the subject forbids that,—but we hope that we may have succeeded so far in mitigating them as to render them not insuperable by those who are accustomed to reasoning on mechanical questions. It is to be regretted that the expansion curve of steam, when expanding without gain or loss of heat, cannot be determined in a simpler way than that adopted in Art. 26. If a graphical method should ever be devised of solving this problem, the theory of the steam engine would be complete without the aid of a differential equation, and the remaining difficulties would be solely due to the novelty and generality of the ideas involved.

In preparing these notes, considerable use has been made of a work,* which appears to be little known in England, by Dr. Zeuner, till recently a Professor in the Polytechnic School at Zurich, a writer already favourably known by the translation, lately executed, of his work on "Valve Gears." Zeuner's work is extremely valuable to the student of the theory of the steam engine, from the fulness and clearness with which certain parts of the mechanical theory of heat are discussed, and from the unsparing labour which has been bestowed on the wearisome numerical calculations incidental to the subject. Our obligations to this writer will be repeatedly acknowledged in the course of our work.

In dealing with the "second principle" we have followed a course resembling that adopted by M. Verdet, in his well known "Exposé de la théorie mécanique de la chaleur,"†

* "Grundzüge der mechanischen Wärmetheorie," von Dr. Gustav Zeuner. Leipzig, 1866.

† "Leçons de chimie et de physique." Paris, 1862.

considering at some length the theory of a perfect gas engine before attempting an explanation of the second principle itself. It appears to us that this method admits of being made as logically accurate as any other, while it certainly possesses great advantages in point of simplicity.

In Art. 11 we have calculated the amount of heat requisite to keep steam dry as it expands; and finding it always positive, we have inferred that condensation must take place when steam expands without gain or loss of heat. We have not been able to find anywhere this simple method of demonstrating the well-known fact, all demonstrations that we have seen depending on a knowledge of the adiabatic relation.

We shall be glad if our work be accepted as a contribution towards a really elementary statement of the mechanical theory of heat; and we hope it may be of service to students of this important subject, more especially in its application to the theory of the steam engine. After what has been said, it is hardly necessary to state that these notes form but a part of the instruction in this subject actually given in the Royal School of Naval Architecture and Marine Engineering.

Royal School of Naval Architecture,
November, 1871.

ON THE THEORY OF

THE STEAM ENGINE.

UNITS OF MEASUREMENT. PHYSICAL PROPERTIES OF STEAM.

1. From the principle that heat and work are mutually convertible, it follows that quantities of heat may be expressed in foot pounds, and converesely, that quantities of work may be expressed in thermal units. In thermo-mechanical questions it is necessary to have a common unit of measurement for heat and work, and in Rankine's work the foot pound has been adopted, but the thermal unit might likewise have been adopted, in which case quantities of work would be expressed in thermal units by dividing by 772: thus, 1-horse power is represented by $\frac{33000}{772}$ or 42·75 thermal units per minute. This mode of measurement possesses the advantage of leading to smaller numbers than the other; but, nevertheless, it will be seen hereafter that the foot pound is the most convenient unit.

In measuring temperature we employ Fahrenheit's scale as the one in common use, although the centigrade scale is far more convenient, and it is to be hoped may ultimately be adopted.

2. The density of a vapour or gas is best measured by the volume which one pound of it occupies, for which the convenient term "specific volume" is used by Zeuner. In the case of saturated steam the specific volume is given by the approximate formula $pv^{\frac{17}{16}} =$ constant, up to a pressure of 120 lbs. per square inch. (Rankine, p. 403.) The elaborate calculations of Zeuner have fully confirmed this formula as representing with accuracy the density of steam as calculated from the relation existing between its latent heat of evaporation, temperature, and specific volume.

According to him, the agreement (from .5 to 14 atmospheres) is almost exact, if the index 1·0646 be used in place of Rankine's index $\frac{17}{16} = 1·0625$. (Mechanische Wärme Theorie, p. 294.) The value of the constant is about 475, if the pressures be in pounds per square inch, and the volumes in cubic feet. If we employ Zeuner's index, the formula, when adapted to logarithmic computation, becomes

$$\log v = 2.516 - .939 \log p$$

On account of the difficulty of obtaining steam in a perfectly dry and saturated condition, the density of steam can hardly be said to have been determined experimentally in a thoroughly satisfactory manner. The best experiments are those made by Fairbairn and Tate, who have given the following formula to represent them :—

$$v = ·41 + \frac{389}{p - ·35}$$

where v is the specific volume in cubic feet, and p is the pressure in lbs. per square inch. This formula is very convenient in calculation, but can only be used for pressures between about 20 and 60 lbs. per square inch (absolute): below 20 its results are much too large, above 60 they are much too small. (Comp. Art. 24.)

The density of steam is likewise frequently measured by its "relative volume," that is, by the ratio which its volume bears to the volume of the water from which it was produced. To obtain the relative volume we have simply to multiply the specific volume by 62.5.

The complex relation between the temperature and pressure of saturated steam can only be expressed for a wide range of pressure by formulæ, such as that given by Rankine (p. 237), which require very tedious calculations. For pressures between 6 and 60 lbs. per square inch we may use the formula

$$p = \left(\frac{t + 40}{147}\right)^5$$

where p is the pressure in pounds per square inch, and t is the temperature Fahrenheit. From 60 to 120 lbs. per square inch this formula may likewise be used, but unity should then be added to the result.

Rankine has given a table of the pressure corresponding to a given temperature, but the table unfortunately only extends to every 9° F. For the convenience of students a table is subjoined of the temperature corresponding to a given pressure for every pound on the square inch, from 1