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On the Method of Determining the Best Operating Condition of a Fractionating Oil Diffusion Pump

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1. Introduction

As to Hickman's fractionating oil diffusion pump, it is fundamentally important to study its construction and the quality of oil, on the other hand, the method of determining the best operating condition of pump without an accurate vacuum gauge except a Geisler tube, is also of importance.

It has been of common knowledge on this pump that: (1) the pumping speed has generally a maximum value when end vacuum is the highest, (2) for each boiler there is the best current value which gives the highest end vacuum, hence the overheat is unsuitable, (3) the stable ring-shaped oil figure which appears on the inner surface of the glass wall above the boiler jet of the lowest vacuum side is usually employed as the measure of the best operating condition, and etc.

In this report, it will be shown that for the purpose of determining the best operating condition of Hickman's pump, the method of external measurement of oil temperature is far superior than that of observing the ring-shaped oil figure and the physical meaning of the oil temperature method have been interpreted.

2. Method of Measurements

For simplicity, we shall call the boiler of the 1st, 2nd, 3rd stage and the oil reservoir of Hickman's pump used as No. 1, 2, 3 and 4, each of which has a heater with a resistance of 14.6, 14.6, 14.4 and 9.4 ohms respectively. The vacuum oil used was "B" oil supplied by the Institute of Scientific Research. The currents through heaters were controlled by the aid of "slidacs" for boilers of each stage. Vacuum degrees were measured with a McLeod gauge, the vacuum range higher than 10^-5 mmHg being roughly measured.

3. Ring-Shaped Figure of Oil

The relation between the heating current and the ring-shaped oil figure was first examined in detail. It was observed that, with the gradual increase of the heating current, the oil figure which appeared at first on the glass surface above the No. 1 jet, rose gradually and became horizontal, as is shown in Fig. 1. The more the boiler was heated, the more the oil figure rose, and finally got out of shape by the oil falling along the glass wall. The lower part of the oil figure was always flowing down. When the figure got out of shape at the upper part of the wall, it became inverse crown-shaped or very uneven according as the oil flow was quiet or violent. The surface of the glass wall appeared to be wet with the oil above the ring and dry below it.

Fig. 1. Typical change of the ring-shaped oil figure.

It is considered to be probable that the oil figure seemed to be ring-shaped since at some height the oil falling along the wall
stayed and had a particular thickness, and since the oil vapour coming from a boiler with some kinetic energy and heat capacity, did not condense below the location of the ring but condensed only above it, on account of the relative relation between the temperature of the vapour itself and that of the glass wall. Accordingly, the oil ring figure may be considered to be an equithermal curve on the glass wall. Now, the reason why the ring slanted before becoming horizontal, is the uneven distribution of temperature at the same height of the vertical glass pipe, which was due to the construction of the pump. Hence, as the ring rose, it became horizontal owing to the less temperature difference. The ascension of the ring with the increase of heating current was a natural phenomenon, on considering the increase of the kinetic energy of vapour and the elevation of glass wall temperature.

When one operated each boiler separately, a similar ring appeared, though very faintly, in No.2 and No.3 as in No.1. In these cases, the oil flow was not suited to form a clear ring figure, since the glass pipe with the jets in No.2 and No.3 inclined downwards. The appearance of the rings behind the jets in No.2 and No.3 is considered to show the back flow of vapour into the higher vacuum side owing to the wide gap between the jets and the wall. When one operated three boilers simultaneously, however, the rings in No.2 and No.3 disappeared according to the increase of wall temperature.

In order to know whether one can use the ring figure in No.1 as the measure of the best operating condition or not, the relation between the ring figure and the vacuum degree was observed systematically in both cases of good and bad forevacuum. The results shown in Fig.2 and Fig.3 respectively were obtained. In these figures, figure (1) is the case where only No.1 was operated with variable current, figure (2) is the case where the current of No.1 was fixed constant and that of No.2 was varied, and figure (3) is the case where those of No.1 and No.2 were fixed at the same value and that of No.3 was varied.

(a) Forevacuum: $1 - 2 \times 10^{-2}$ mm Hg.

(b) Forevacuum: $4 - 5 \times 10^{-3}$ mm Hg.

Fig. 2. Change of the ring-shaped oil figure. The numerals express the current values (in amp.) in variable boilers.

(a) Forevacuum: $1 - 2 \times 10^{-3}$ mm Hg

(b) Forevacuum: $4 - 5 \times 10^{-3}$ mm Hg

Fig. 3. Relation between vacuum degree and heating current.
Case (1): It was observed that the ring figure was most stable and regular at the current of about 1.7 amps. On the other hand, as shown in Fig. 3, the highest vacuum was obtained at 2 amps., being a little larger than the former value.

Case (2) (Current in No.1, \(i_1=2.0\) amps. fixed.): A stable regular ring appeared at 2 amps. with the highest vacuum.

Case (3) \(i_1=i_2=2.0\) amps. fixed.): Both a figure and a vacuum degree remained almost unchanged, in spite of changing the current in No.3.

From the above observations, it may be seen that, when the forevacuum is good, the stable regular ring and the highest vacuum are obtained by nearly the same heating current.

(b) Forevacuum: \(4\sim5\times10^{-3}\) mmHg.

Case (1): The current value at which a figure appeared was larger than that in case of (a), (1). This happened, probably because the vapour lost its energy more rapidly in frequent collisions with air molecules, and condensed on the lower part of the wall. In conformity with the above, it was observed that, by stopping the oil-rotary pump, the ring fell gradually and after several minutes disappeared entirely. Unlike the case of (a), another figure appeared at the upper part of the wall independently of the normal one, as shown in the figure. This figure always had an irregular shape. Both rings appeared simultaneously, probably because oil consisted of two components with different heat of vaporization. In case of (a), the position of the upper figure will be too high for its appearance. The vacuum degree was the highest near the current value at which such two rings appeared, however, the upper one was unstable.

Case (2) \(i_1=1.7\) amps.: Similarly to (1), rings appeared in two stages at 1.8 amps. where the highest vacuum was obtained. The upper figure was less unstable comparing with (1).

Case (3) \(i_1=i_2=1.7\) amps.): As the current of No. 3 increased, the ring descended gradually and disappeared, accompanying the small change of the vacuum degree.

Judging from the above description, it seems to be undesirable always to rely on the stable regular oil figure as the measure of the best operation, since the current value at which such a oil figure appears does not correspond to that of the highest vacuum except when the forevacuum is satisfactory.

In the above, the cause of the ring formation and its change with the current have been interpreted as mainly due to the glass wall temperature, but they may also be interpreted by considering that the pressure of rising oil vapour compensates the force of the oil falling along the wall. It was observed that the figure rose and fell rapidly with the boiling of oil. To such a phenomenon, the latter interpretation is considered to be more suitable rather than the former. It may be somewhat difficult, however, for the latter to explain the cause of the appearance of two rings above described, and of ring at No.2 or No.3 boiler operated separately.


The measurement of oil temperature in relation to the change of heater input current was performed. From outside-of-glass bulb, the oil temperature was indirectly measured with the mercury thermometer located in the hollow of the bulb at the exit of heater leads. Fig. 4 shows the plot of the oil temperatures of each boiler to the heater input powers. Each of curves from (1) to (6) in (a) and (b) are showing the oil temperatures of the following boilers:

(1): No.1 (when only No.1 was operated),

(2): No.2 (when the current of No.1 was fixed constant and that of No.2 was varied),

(3): No.3 (when the currents of No.1 and No.2 were fixed constant at the same value and that of No.3 was varied),

(4): No.1 (the same as case (2)),

(5): No.1 (the same as case (3)),

(6): No.2 (the same as case (3)).

(a): Forevacuum: \(1\sim2\times10^{-3}\) mmHg.

In the case of only No.1, the temperature-input curve shows a concave deviation from a monotonous curve, as shown in curve (1). Comparing the above curve with the curve of vacuum degree ((1) in Fig. 3, (a)), it may be seen that the best vacuum appears near the current value (2.0 amps.)
corresponding to the point of inflexion in the former curve. Similarly, in curve (2) obtained with the current of No.1 fixed constant near this value and changing the input current of No.2, a point of inflexion appears near the current value (2.0 amps.) corresponding to the highest vacuum degree. When the currents of No.1 and No.2 were fixed constant and No.3 was varied, however, there existed no such concave deviation.

(b) Forevacuum: 4~5 x 10^{-3} mmHg.

Similarly to the case of (a), curves (1) and (2) show a point of inflexion at the current values corresponding to the highest vacuum degree, and curve (3) is monotonous, as shown in Fig. 3, (b).

It seems remarkable that, as stated above, the current values corresponding to points of inflexion in temperature-input curves nearly agree with those which give the highest vacuum degrees, though there exist the differences of less than 0.1 amp. Similar results were also noticed in cases of the other various combinations of boilers. This fact may be explained as follows: the temperature-input curve deviates downwards remarkably from a straight line, since the heat loss due to the vaporization of oil is greater than that due to the conduction or to the radiation, and the point of inflexion appearing in monotonous curve corresponds to the current at the highest vacuum degree, since at this current value the vaporization is most active for input power, that is, most effective.

The temperature curve for No.1 (or No. 1 and No.2) has a tendency to descend, when the current of No.1 (or No.1 and No.2) was fixed constant and the current of No.2 (or No.3) was changed (Fig. 4 (a), (b), curve (4), (5) and (6)). This may probably happened because, by increasing the current in a variable boiler, the circulation of oil in the pump became gradually active, and the amount of vaporization in the boilers of constant input somewhat increased.

In the current region corresponding to the concave deviation, the temperature of oil increased in the order of No.1, 2 and 3 for the same input. This can be easily explained by considering that the heat loss due to vaporization was less in the above order, as in this region the fractionating action was so effective that the density of oil collected in each boiler increased in that order.

5. Conclusion

As stated above, the stable ring-shaped oil figure can not be the measure of the best condition of Hickman's pump when the forepump works ineffectively. Even in such cases, however, if one measures the temperature change of oil relative to input power from outside of boilers, the current value corresponding to the point of inflexion in the curve gives nearly the highest vacuum degree. By this method, therefore, even without vacuum gauge one can easily
find the appropriate current value for the best efficiency of the pump. The most suitable current may be determined for each boiler in succession, first No. 1 and then No. 2, etc. After the resistances have been so combined that the most suitable current flows into each boiler respectively, one may start the pump. After all, it is concluded that the method of the external measurement of oil temperature is far superior than the usual ring figure method, for determining the best operating condition of Hickman’s pump.

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Summary
(a) On Hickman’s pump, it seems to be undesirable always to rely on the stable regular oil figure as the measure of the best operation, since the current value at which such a oil figure appears does not correspond to that of the highest vacuum except when the forevacuum is satisfactory.

(b) Even in the case of unsatisfactory forevacuum, the current value of the highest vacuum may be determined by the point of inflexion in the curve representing the change of oil temperature measured from outside of the bulb relative to the input power of boiler. By this method, therefore, even without a vacuum gauge one can easily find the appropriate current value for the best efficiency of the pump.

References
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