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Temperature and Fluid Property Effects on Cavitation in Aircraft Fuel Pumps

by

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TEMPERATURE AND FLUID PROPERTY EFFECTS ON CAVITATION IN AIRCRAFT FUEL PUMPS

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SUMMARY

The effects of temperature and fluid properties on pump cavitation performance are discussed. Consideration is given to the problems of measuring net positive suction head and a novel test technique is described for examining cavitation performance using a closed loop system. Results are presented for a small booster pump operating in water and kerosine fuel; these confirm the theoretical prediction that less net positive suction head is required to pump the fluids satisfactorily when at elevated temperatures than when cold. In conflict with theory the pump performance with kerosine is inferior to that with cold water as net positive suction head is reduced. It is believed this may be due to the difference in air solubility between the two fluids.

The prediction of pump cavitation performance in aircraft fuels from tests with other fluids is considered. Because of the influence of dissolved air content and the dependence of the vapour pressure of multi-component fluids on vapour/liquid ratios, it is concluded that prediction is unlikely to be feasible.

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1 INTRODUCTION

Numerous attempts have been made in recent years to assess the effects of fluid properties and fluid temperature on the cavitation performance of pumps. Much initial pump design is based on cold water performance because of the ready availability and ease of handling of this medium. However, it is known that pumps operating on fluids such as hydrocarbons or hot water may perform satisfactorily when supplied with less net positive suction head (NPSH) than that required for cold water. The NPSH is defined as the difference between the absolute total pressure head at the pump inlet and the fluid vapour pressure head at the fluid temperature; essentially it is a measure of the proximity to boiling of the fluid. For any particular pump and fluid operating condition there exists a minimum NPSH at which cavitation bubbles commence to form, corresponding approximately with the situation where the minimum local static pressure occurring on the suction face of the pump impeller blading equals the fluid vapour pressure. The presence of these voids in the fluid reduces the flow capacity and interferes with the head raising ability of the pump. The effect of cavitation is progressive as the NPSH is reduced below the value at which cavitation inception occurs, and the rate of fall off in performance is governed by the ability of the pump to handle two phase flow. Complete breakdown in performance may occur abruptly after the inception of cavitation bubble growth, but with suitable design the reduction in performance may be delayed so that the pump continues to operate well into the cavitation régime although at reduced capacity and head rise.

It is evident that cost and development time would be saved if one could predict pump performance with fluids at elevated temperatures, and with different fluids, on the basis of cold water tests alone. The R.A.E. interest in the effects of fluid properties and temperature on cavitation in pumps arose during the development of a test facility for examining the performance of aircraft fuel booster and transfer pumps under conditions simulating high altitude, high speed flight where the proximity of the fuel to boiling meant that the pumps would be cavitating. The rig was designed to be representative in scale of a Concorde fuel tank having a capacity of 1000 gallons. Because of the large fuel volume and the safety problems involved in handling and disposing of hot kerosine fuel it was hoped originally that water could be used as the test fluid for examining the performance of Concorde pumps and that it would be possible to predict the performance with kerosine.

An examination of the literature pertinent to cavitation scaling, fluid property and temperature effects suggested that no entirely satisfactory prediction method existed and therefore kerosine has always been used in the R.A.E. pump test rig. However, a small research programme was started with the object of assessing whether it would be feasible to devise a prediction method for kerosine pumping performance on the basis of water test data. Particularly at NASA[1] progress has been made on prediction methods for single component fluids and a number of workers elsewhere have endeavoured to devise methods for single and multi-component fluids including hydrocarbon mixtures[2]. The methods suggested have not yet achieved general acceptance in industry and it is still common practice to base design on tests with pumps handling the actual liquid for which they are intended. This is particularly understandable in the aircraft industry where fuel tank pump performance is bedevilled by the presence of large quantities of air held in solution in the fuel and the previous history of subjection to altitude, temperature and agitation is of critical importance.

This Report describes a novel test technique for examining pump cavitation performance with different fluids whereby the effects of fluid properties and temperature on NPSH requirements may be determined with greater accuracy than in much previous experimental work. Some results are presented for water and kerosine fuel. A review of some of the experimental difficulties involved in cavitation testing of multi-component fluids is made and it is concluded that, because of the influence of dissolved gas content and the dependence of the vapour pressure of multi-component fluids on the vapour/liquid volume ratio, it is questionable whether a method of practical value to the aircraft fuel pump designer can be devised to enable cavitation performance to be predicted from tests with other fluids.

2 EFFECT OF FLUID PROPERTIES AND TEMPERATURE ON PUMP CAVITATION PERFORMANCE

Qualitative explanations of the phenomena associated with the NPSH requirements for pumping fluids at elevated temperatures, and for pumping fluids other than cold water, have been suggested by a number of authors including Stepanoff[3], Spraker[4], Salemann[5], Jacobs[6], Jakobsen[7] and Ruggeri[8].

To explain the influence of fluid properties and temperature on the NPSH performance of pumps it is first postulated that the fluid contains a number of nuclei on which cavitation bubbles may grow. Generally these nuclei are present in the form of minute bubbles of undissolved gas, or gas liberated from a supersaturated solution, or in the form of particulate contaminants having a film or pockets of adsorbed gas on the surface. Within the passages of a pump impeller local regions of reduced static pressure occur, and when fluid enters these regions the boiling point of the fluid drops by, say, ΔT. Assuming that the local fluid temperature is in excess of the fluid boiling point appropriate to the local low pressure, evaporation commences, possibly into the minute bubbles of undissolved gas acting as nuclei. Once the surface tension forces have been overcome the cavitation bubbles start to grow. The heat required to produce the vapour content of the bubbles is drawn from the fluid layer adjacent to the vapour/liquid interface of the bubbles. The residence time of the fluid in the low pressure regions is dependent on the flow rate, and bubble collapse occurs when the bubbles are swept into regions of higher pressure. In general the residence time is short and it is to be expected that the fluid layer involved in the vaporisation process will be very thin. The amount of vapour formed depends on the amount of heat which can be extracted locally, and is a function of the thermal diffusivity and latent heat of vaporisation of the fluid, together with the flow conditions. The extraction of heat from the fluid adjacent to the bubbles results in a local temperature depression, probably somewhat less than ΔT, and the vapour pressure within the cavitation bubbles is consequently lower than that associated with the bulk fluid temperature. Because of this depression in vapour pressure the local NPSH is effectively higher than that based on the vapour pressure of the bulk fluid at its temperature remote from the cavitating zone. Provided there is no cavitation it appears reasonable to assume that pump performance is independent of NPSH; however, with reduction in NPSH, for any given set of flow and pressure rise conditions a point is reached where cavitation starts and performance becomes dependent on NPSH. Irrespective of fluid, or fluid temperature, it is assumed that the critical NPSH at which dependence starts is constant for any given pump. It is evident that a reduction in NPSH, below the critical value, results in cavity formation which is a function of fluid properties and flow conditions, and one would not expect the pump performance to remain the same with different fluids at different temperatures for the same NPSH based on bulk fluid temperature.

Consider the performance of a pump operating with the same fluid, at the same NPSH based on the bulk fluid temperature, but with the fluid at two different temperatures. Suppose the NPSH is reduced by ΔNPSH below the critical value so that cavitation occurs. Then the depression arising in the vapour pressure in the cavitating zone is directly proportional to ΔNPSH and has the same value in both cases. For all fluids the shape of the saturation vapour pressure/temperature curve is such that dp_v/dT increases strongly with temperature. Consequently the local temperature depression, corresponding to the vapour pressure depression, must be smaller with the higher temperature fluid than with that at lower temperature. For a temperature depression dT the volume of vapour formed is

$$V_v = \frac{\rho_e V_e c_p dT}{\rho_v L}$$

where ρ_e is the fluid density, ρ_v the vapour density, c_p the specific heat of the fluid at constant pressure, L the latent heat of vaporisation and V_e the volume of fluid associated with the evaporative process. With increasing temperature the specific heat and vapour density of all fluids increase and the latent heat of vaporisation and the liquid density decrease. Of these fluid property variations with temperature the increase in vapour density with temperature is dominant and by comparison the other variations are negligible. The volume of liquid associated with the evaporative process is dependent upon a time scale related to the residence time of the fluid in the low pressure region, and on the thermal diffusivity of the fluid. For a small ΔNPSH it is reasonable to assume that the flow rates, and hence residence times, will only differ slightly in the two cases. The thermal diffusivity defined as $k/c_p \rho_e$, where k is thermal conductivity, varies little with temperature since k, c_p and ρ_e are all rather weak functions of temperature. Thus, for a particular fluid, the volume of liquid V_e is expected to change only slightly with temperature and the dominant parameters in the expression for vapour volume V_v are ρ_v and dT, and V_v is approximately proportional to dT/ρ_v. Because dT decreases with increasing temperature and ρ_v increases, the volume of vapour formed as a result of the ΔNPSH change is smaller for the fluid at the higher of the two fluid temperatures. This approach qualitatively explains why a pump performs better at NPSH values, below those appropriate to incipient cavitation, when it is handling a fluid at high temperature.

It seems physically reasonable that a pump should perform better when handling a low ratio of vapour to liquid but it does not follow that a pump will operate in an identical manner with fluids of different properties provided that the local vapour/liquid ratio is the same. To produce the same vapour/liquid ratio it is necessary to adjust the pressure conditions and this may affect the velocity distribution in the pump; the flow may no longer be similar in the two cases and the cavitation mode may differ (see for example Ref.5). To date, no satisfactory means of establishing the local vapour/liquid ratio in the passages of a rotating impeller has been established. To progress from the qualitative approach explaining the behaviour of a pump handling fluid at two different temperatures to a method of predicting NPSH performance it is necessary to make some assumption regarding similarity of the flows and that commonly made: that the pump performance should correspond at the same vapour/liquid ratio, is not completely acceptable, although it may be reasonable for some cases.

A similar approach to that preceding may be used to establish that it should be easier to pump other fluids with less NPSH than is required for cold water. Insertion of corresponding numerical values for the fluid property parameters involved in the expression for the volume of vapour formed, as a result of an NPSH reduction below the cavitation inception value, shows that most vapour is formed with cold water. Consequently a pump is liable to perform better at low NPSH values when operating on fluids other than cold water; a practical implication of this is that a pump designed on the basis of cold water tests may be overdesigned for use with other fluids.

The early impression gained from the literature was that pumping cold water at very low NPSH values was likely to present the most severe test for a pump and, if an aircraft fuel pump performed satisfactorily at the required NPSH value with water, it seemed reasonable to assume that the behaviour with fuel at the same NPSH would be somewhat better. This was particularly suggested by the work of Spraker[4] who found that the NPSH required for pumping mixed hydrocarbon fluids was not only less than that for pumping cold water but also less than that for pumping single component fluids with similar theoretical vapour/liquid ratios. His explanation for this behaviour was that in a single component fluid the entire interface between bubble and liquid is available for vaporisation, whereas in a mixed fluid the vaporising component is only a small percentage of the total and this light fraction must diffuse through unvaporised constituents in order to form a bubble. Consequently bubble growth is retarded relative to the single component fluid situation. Contrary to Spraker's results Salemann[5] found that the performance of a pump handling degasified kerosine at 70°F was the same as with water at 70°F, but when pumping gasoline at 70°F a higher NPSH was required than for water to give comparable cavitation performance.

To some extent there is a lack of reality in the theoretical approach adopted to explain the effect of fluid properties on pump performance. Experience with pumping kerosine and other hydrocarbon fuels suggests that the dissolved air content can be a dominant factor in establishing NPSH performance. All fluids normally contain a certain amount of dissolved air and the mass of air in solution at saturation is proportional to the pressure of the air in contact with the fluid (Henry's law). The quantity of air in solution at saturation depends upon the fluid; for example, at 15°C and 760 mmHg pressure water contains about 2% by volume whereas kerosine contains about 15%. In high altitude flight kerosine fuel in aircraft tanks tends to retain its air content by mass, appropriate to saturation at sea level conditions, and becomes highly supersaturated. Aircraft vibration, flight manoeuvres and agitation by fuel pumps reduce the degree of supersaturation but flight tests have shown that equilibrium conditions may not be established even after several hours flight at constant altitude. Consequently, fuel entering the low pressure regions of a pump impeller may be highly supersaturated with air and a gaseous form of cavitation, as opposed to vaporous cavitation, tends to occur. In general cavitation bubbles contain both air released from solution and fluid vapour but the relative amounts depend on the state of non-equilibrium: with a near boiling fluid the cavitation may be predominantly vaporous, but gaseous cavitation may prevail with fluid in conditions far removed from boiling. To date little attention has been paid to the predominantly gaseous form of cavitation and the effect of fluid properties and temperature on this phenomenon. However, particularly with aircraft fuels, the subject is important and pump design to cope with gaseous cavitation may be more critical than for vaporous cavitation. Specific problems have occurred with aircraft fuel pumps required to start at high altitude, where the fuel has been supersaturated with air, and pump failures have occurred although the pumps have been quite capable of performing satisfactorily with degassed boiling fuel. In these conditions the relevance of NPSH as a pump performance parameter is in doubt and it is questionable whether it is meaningful. The problem is not unique to aircraft fuel pumping but is prevalent in the hydrocarbon processing industry[9].

Much experimental data has been accumulated over recent years on the comparative performance of a number of pumps operating in cavitating conditions on various fluids over wide temperature ranges. A variety of methods of correlation of the results has been attempted in efforts to substantiate proposed prediction methods but unfortunately there has been little uniformity of test technique and the accuracy of measurement of parameters such as NPSH or the NPSH depression below a datum value has left much to be desired; this has resulted in a very wide scatter of experimental points. It is pertinent at this stage to consider some of the experimental problems.

3 PROBLEMS OF NPSH MEASUREMENT

The principal experimental difficulty involved in examining the NPSH performance of pumps lies in the accurate determination of NPSH or the deviations of NPSH from a datum value usually associated with cavitation inception. The measurement of NPSH requires the monitoring of total pressure at the pump inlet and of fluid vapour pressure. The vapour pressure may be determined directly or derived from a temperature measurement in the case of a single component fluid with known vapour pressure/temperature characteristics. However, as the temperature increases, the slope of the saturation pressure/temperature curve is such that a large change in vapour pressure often corresponds to a small change in temperature. For example, with water at 15°C a change in temperature of 1°C corresponds to a change in vapour pressure head of approximately 0·43 inch, whereas at 100°C a similar temperature change corresponds to a head of approximately 14·5 inches. Since there exist small temperature gradients in a cavitating flow system and, because of low thermal conductivity and incomplete fluid mixing, there may be some temperature stratification in the fluid circuit there must always be some uncertainty involved in the measurement of the appropriate fluid temperature or vapour pressure. Experimentally recorded NPSH depressions due to temperature and fluid property effects are generally of the order of one foot so that a bulk temperature measurement inaccuracy could easily mask an NPSH change or produce a spurious effect. A direct vapour pressure measurement also presents problems in that it must be made at the correct fluid temperature and heat transfer to and from the sample maintained in equilibrium in the course of measurement. However, at low temperatures where the fluid vapour pressure is very low in comparison with pump inlet pressure, the NPSH can be determined with a reasonable accuracy, the same numerical accuracy being increasingly difficult to obtain as the vapour pressure increases with temperature.

The methods used by both Spraker[4] and Salemann[5] for determining NPSH are open to criticism. Spraker used a variant of the vapour bulb technique devised by Jacobs, Martin and Hardy[10] for use with cryogenic fluids which have a very low dissolved gas content; Salemann also attempted the vapour bulb method but, because of experimental difficulties, abandoned it in favour of separate measurement of pump inlet pressure and vapour pressure. For hydrocarbons Salemann derived vapour pressure by Reid and bubble point methods and the results indicate the presence of dissolved gas: this might have accounted for the trend of NPSH when pumping hydrocarbons. Essentially the apparatus used by Spraker for direct NPSH measurement consisted of a mercury filled U-tube one side of which was connected to the pump inlet pressure tapping and the other side to the vapour bulb. A sample of the pump test fluid was introduced into the vapour bulb which was situated in the pump inlet area so that its temperature was ostensibly that of the fluid being pumped. When the vapour bulb was filled so that the test fluid was in contact with the mercury in the U-tube it was sealed off. As the pump inlet pressure was reduced so also was the pressure on the fluid sample in the vapour bulb, and the fluid vaporised, exerting the vapour pressure appropriate to the fluid temperature. The movement of the column of mercury then gave a direct measurement of the difference between pump inlet pressure and fluid vapour pressure, i.e. NPSH.

For single component fluids the vapour bulb method appears quite satisfactory provided that the sample and the pumped fluid are at the same temperature and their dissolved gas contents are negligible. In the case of multicomponent fluids the light fractions vaporise first and the vapour/liquid ratio in the vapour bulb increases with temperature and reduction of pump inlet pressure. The vapour pressure of a multi-component fluid is only meaningful if the V/L ratio is specified: as V/L is increased more of the volatile constituents pass into the vapour phase and the vapour pressure of the residual fluid decreases. True vapour pressure is defined as the pressure exerted as V/L tends to zero and it may be noted that the vapour pressure of a single component fluid is independent of V/L ratio. Because of the dependence on V/L ratio of the vapour pressure of a multi-component fluid the meaningfulness of NPSH derived by the vapour bulb method is questionable. Assuming the effect of V/L change on vapour pressure is known it is possible to apply corrections but the problem is complicated when, as in Spraker's arrangement, movement of the mercury column alters the total volume of the vapour bulb. Recent work by Ross[11] on kerosine fuels suggests that for AVTUR the vapour pressure decreases by 0·4% per unit increase in V/L up to V/L = 19, whereas for the less volatile AVCAT the decrease is 0·1% per unit increase in V/L. The mixed fluids used by Spraker seem to have been more volatile than AVTUR and to have had vapour pressure, at the test temperatures, in excess of 20 in Hg. If it is postulated that NPSH should be based on true vapour pressure, and a

0·4% decrease per unit increase in V/L is considered, then a V/L ratio of about 8 with a vapour pressure of 20 in Hg would account for a recorded NPSH one foot higher than the true NPSH and the error would increase with temperature and vapour pressure. It is evident that the effect of V/L ratio could be significant and is closely related to the dimensions of the apparatus and the sample volume, together with the pressure measuring technique. Jacobs, Martin and Hardy[10] used a differential pressure transducer instead of a mercury manometer and this has the merit of retaining a constant volume for the vapour bulb.

Although potentially significant the effects of V/L ratio on NPSH measurement are probably far less serious than the consequences of the presence of dissolved gas in the sample in the vapour bulb. Ross[11] shows the effect of not removing dissolved air and normal acceptable water content from samples of AVTUR on the total pressure recorded with a vapour pressure measuring apparatus very similar to a vapour bulb: at 60°C with V/L = 1 the total pressure was 192 mmHg whereas when dried and degassed the total pressure was 31·5 mmHg; the corresponding pressures at 140°C were 592 mmHg and 362 mmHg. If the vapour bulb technique is to lead to a correct NPSH measurement it is evident that the sample in the bulb, and the test fluid, must be substantially free of dissolved gas otherwise the possible error in NPSH may be several feet, particularly if the test fluid happens to be gas-free and the bulb sample aerated: in this case the error would be such that the recorded NPSH would be lower than the true NPSH. Because air in the vapour space of a vapour bulb would obey the gas laws the NPSH error would vary with temperature and bulb vapour volume, thus leading to consistent spurious effects possibly masking real effects.

Insufficient detail is given in Spraker's paper[4] to say whether his test or bulb fluids were degassed but it is stated that some vapour pressures for water and methyl alcohol derived via the bulb technique and compared with published data were erroneous, apparently as a result of dissolved air: this suggests a similar possibility with the mixed hydrocarbon fluids. Since Spraker used a closed rig operating initially at atmospheric pressure it is highly probable that the test fluid would have been air saturated and the amount of air released from solution would depend on the local pressure drops in the system: this air would then be reabsorbed. Spraker endeavours to prove that his NPSH measurements on mixed hydrocarbon fluids are correct by deriving from these, and separate inlet pressure measurements, the vapour pressure of the fluids at three temperatures and demonstrating that the derived vapour pressures for each fluid plot as a straight line on semilog paper as a function of the reciprocal of the absolute temperature. Although only three temperatures were used the vapour pressure at each of these temperatures was derived from a number of NPSH measurements. Spraker's proof is plausible for the vapour pressure would not produce a straight line relationship unless a constant V/L ratio was used; it is of course quite possible that the presence of dissolved air would counteract the V/L ratio effect quite consistently. There are thus some grounds for scepticism concerning the validity of Spraker's results.

The preceding comments are not so much intended as criticism as to indicate the difficulties involved in producing experimental techniques appropriate for examining the cavitation performance of pumps operating with kerosine or other mixed hydrocarbon fluids, even when substantial degassing is possible and the supersaturation of the bulk fluid at reduced pressure conditions is eliminated. The high dissolved air content of aviation fuels when saturated strongly suggests that gaseous cavitation effects may be more important than vaporous cavitation.

4 TEST TECHNIQUE AND APPARATUS

A test method has been devised at the R.A.E. which attempts to avoid the problems of measuring vapour pressure and temperature for determining NPSH. The principle entails the use of a closed system partially filled with test fluid and capable of being evacuated to a very low pressure. In a closed system at low pressure a datum NPSH can be established with a fixed static head of fluid above a pump inlet and NPSH changes effected by varying this head. If the fluid temperature in the system is raised the datum NPSH remains constant subject to corrections arising from the expansion of the fluid and compression of the air in the system ullage. Changes from the datum NPSH can again be effected by varying static head at the elevated temperature. By operating at low initial pressure with the cold fluid the corrections necessary can be minimised in comparison with the NPSH. The absolute NPSH then differs only slightly from the fluid static head.

The experimental arrangement is shown schematically in Fig.1. The system forms a closed loop which may be evacuated to the desired pressure and isolated from the vacuum pumps. The test tank in which the pump is mounted has a capacity of approximately 2 cu ft and the header tank a capacity of approximately 7 cu ft. Adjustment of the valve between the header and test tanks enables a constant static head of fluid to be maintained above the pump inlet. The height of the test tank has to be matched to the pump NPSH performance in the sense that the NPSH variation possible by adjusting the fluid static head must approximately correspond with the NPSH change between cavitation inception and flow breakdown. In the tests made the pump used was a small aircraft fuel booster pump Type FBX Mark 9 made by the Pulsometer Engineering Co. Preliminary tests showed that the pump required an NPSH of approximately 2 ft for cavitation to manifest itself visually when operating at 6000 rev/min on cold water (12°C). The pump is intended for tank mounting with the impeller facing upwards into the fluid so that the flow is directly into the pump inlet without need for a suction line. It was somewhat fortuitous that the height of the test tank almost perfectly matched the pump NPSH for cavitation inception. If the pump NPSH had been say 10 ft, a 10 ft high test tank would have been needed. It was found that the cavitation process beyond the inception stage was interfered with by a column of air which was drawn into the eye of the impeller at low NPSH values with a fluid static head of about one foot. This interference was eliminated by mounting a conical baffle above the impeller which prevented air entrainment until the tank was virtually empty.

Tank pressure was measured using a mercury manometer and a Bourdon gauge to act as a cross check; pump delivery pressure was measured with a Bourdon gauge and flow rate with a turbine flowmeter. The sight glass on the test tank was calibrated to give fluid static head above the pump impeller. The fluid temperature was measured at three points within the system and the whole was lagged with glass fibre insulating material to minimise heat losses and temperature gradients in the circuit.

In operation the header tank was filled completely so that when the test tank was full the vapour space in the system was approximately 2 cu ft. Fluid was circulated by the pump whilst the system was evacuated by the vacuum pumps. In practice the vacuum pumps were capable of reducing the pressure to within 0·2 to 0·4 in Hg absolute so that with water at 15°C, with a vapour pressure of about 0·4 in Hg, surface boiling occurred and the majority of dissolved air originally present was released from solution. With kerosine surface boiling occurred momentarily for some samples and the evacuation process undoubtedly led to the loss of some light fractions; substantial degassing occurred during evacuation. When air bubbles ceased to be evolved the shut-off valve in the vacuum line was closed and the system isolated so that NPSH could be varied by changing fluid static level only. The pump performance with varying NPSH was then recorded. Prior to all tests great care was taken to ensure that the system was 'vacuum tight' and that there was no leakage; this was a major problem because the circuit was constructed from available pipes and fittings not specifically intended for working at moderate vacuum levels. Nevertheless a reasonable state of tightness was achieved and at minimum pressure the inward leak rate was kept to about 0·1 in Hg over a period of three hours. After recording pump performance with the operating fluid cold the steam heating system was turned on and the fluid temperature raised and stabilised at the desired test temperature with all three thermometers giving identical readings. Because the system is closed the effect of raising the fluid temperature is merely to change the vapour pressure and consequently the tank total pressure by a corresponding amount, without affecting the bulk NPSH. However, in practice the NPSH is changed from the datum level due to thermal expansion of the fluid and compression of the air remaining in the ullage space in the system at the elevated temperature. Since the initial volumes involved are known and coefficients of cubical expansion may be obtained from published data the appropriate corrections may be applied. At the absolute air pressure at which the system was operated the maximum correction required with water was approximately 2 inches of water at 100°C, i.e. if the datum level in the system with water at 15°C was the NPSH with a fluid static head of 18 inches then at 100°C the same NPSH would be obtained with a static head of 16 inches. Evidently in designing a system of this type it is desirable that the vacuum plant should be capable of reaching an absolute pressure as low as possible, so as to keep the corrections arising from thermal expansion to a minimum. Also, to be able to cover the required NPSH range without having to use a tall test tank the choice of test pump may have to be somewhat restricted.

5 COMPARISON OF PUMP CAVITATION PERFORMANCE

In cavitation testing of pumps it has become fairly standard practice to establish the change in NPSH required to maintain a desired flow rate when the pump head rise falls by some arbitrary percentage of the head rise given at that flow rate by the pump when operating with ample NPSH in non-cavitating conditions. The arbitrary percentage chosen has varied between 2 or 3% and complete breakdown (100%) according to the interests of the experimenter. This makes it difficult to compare the results obtained by different individuals. A disadvantage of the constant flow rate system is that there comes a point where the limiting system back pressure is such that the flow cannot be maintained constant and falls off, and this point is reached when the flow throttling control valve in the system is wide open. With falling flow rate the cavitation pattern in the pump impeller changes continually as the NPSH is reduced. An alternative procedure is to adjust the throttling valve so as to maintain a constant head rise and to establish the change in NPSH required when the flow rate falls off by some arbitrary percentage of the non-cavitating flow. This has similar disadvantages when the chosen head rise cannot be maintained. In these methods the object is to establish the change in NPSH with either varying flow rate or head rise, and it is tacitly assumed that cavitation similarity pertains in these varying conditions. However, as pointed out earlier this is not necessarily the case and the cavitation modes may differ with temperature of the fluid; consequently any comparison with theory appears likely to be unsatisfactory. Both methods are, however, acceptable for obtaining a comparison of performance.

In the present case the pump head rise was maintained constant and the variation of flow with NPSH observed. In practice this was found to be easier than maintaining constant flow since oscillation of the pump delivery pressure gauge needle made precise readings difficult and maintenance of flow rate at the same time as taking readings, adjusting the fluid level control valve etc. was somewhat impracticable. Consequently the original efforts to achieve constant flow led to an undesirable scatter of experimental points. However, it was relatively easy to maintain constant pump head rise since the pump performance and rig configuration was such that the majority of the head rise attained at the best efficiency flow rate of about 500-550 gal/hr was required to raise the fluid vertically up to the header tank and the circuit losses were very small in comparison. A small change in flow rate thus resulted in little change in friction losses compared with overall head rise and it was found in practice that a single setting of the throttle valve sufficed to maintain substantially constant head. Minor adjustment was required to reset the datum flow value as fluid temperature was increased and viscosity and fluid density reductions affected the system. It may be noted that this arrangement would not have been so easy to operate if the pump delivery head had been of the order of 100 ft instead of 12 ft and back pressure was achieved by throttling valve adjustment.

6 RESULTS

The results of tests with water over a range of temperatures up to 100°C are shown in Fig.2, where flow rate is plotted against NPSH change from the original datum value as produced by varying the head of fluid above the impeller. In these particular tests the datum NPSH was about 22 inches with a static head of 18 inches of fluid above the impeller, i.e. the pump NPSH is approximately fluid head above the impeller plus 4 inches. The results show clearly that fluid temperature has a marked effect on pump performance and, for example, that the performance of the particular pump tested is the same under cavitating conditions when delivering 500 gal/hr with water at 12·5°C and an NPSH of about 17 inches, as with water at 80°C and an NPSH of 7 inches. No attempt is made in this paper to produce a correlation of the experimental results with any of the theories propounded and the results shown are merely intended to indicate the comparative performance of the pump tested.

A few tests have also been made with kerosine fuel (AVTUR 50) using the same pump. Preliminary tests indicated that at temperatures up to 70°C the pump performance deterioration was independent of temperature as the NPSH was reduced. However the pump behaviour with NPSH change differed from that occurring with water and the fall off in performance, as shown in Fig.3 at 19°C, was somewhat more abrupt. This is contrary to what would be expected on the basis of theory and might be due to the presence of larger quantities of dissolved air in the kerosine. In the case of the water tests the dissolved air was largely removed by boiling under vacuum for a period, this is not so easily done with kerosine because boiling removes some of the light hydrocarbon fractions and changes the characteristics of the fuel. Because no temperature effect was evident at 70°C it was decided to make a test with kerosine at the highest temperature compatible with the materials used in the rig. This test was terminated at 120°C when the perspex windows in the test tank began to deteriorate. The results are shown in Fig.3 after the appropriate corrections for thermal expansion of the kerosine have been applied. Evidently there is a temperature effect with kerosine but this is not marked until comparatively high temperatures are reached.

The repeatability of tests with water was found to be good but with kerosine was less satisfactory. It is believed that the variability in the behaviour of kerosine may be due to fuel sample differences and the loss of light hydrocarbons during evacuation of the rig, combined with the effects of residual dissolved air.

7 SOME PRACTICAL CONSIDERATIONS

It seems probable that the performance of pumps operating with single component degassed fluids will be predictable on the basis of tests with water, however there are very few practical instances outside the cryogenic field where such fluids are handled. Aircraft fuels are almost always saturated or supersaturated with dissolved gas. It appears feasible, although practically very difficult, to degas multi-component hydrocarbon fluids in sufficient volume for pump tests to be made. The degassing required can be achieved by freezing the fluid contained in a closed system and evacuating the system to as near zero absolute pressure as possible, heating and agitating the fluid then results in release of dissolved air. If the system is then cooled the light fractions which have vaporised condense and when the fluid is frozen the air released from solution may be pumped off. Repetition of this process results in a substantially gas-free fluid being obtained from which the lighter hydrocarbons have not been removed. Pump tests then have to be made in a closed rig without allowing the test fluid to come into contact with any gas which may be absorbed. By this means it should be possible to examine the effects of fluid properties on the purely vaporous cavitation in a pump. The introduction of a known quantity of air into the system may then enable the combined effects of vaporous and gaseous cavitation to be studied.

Grave doubts must be expressed regarding the possibility of predicting the performance of pumps operating on multi-component fluids and fluids with high dissolved gas contents because the idealised test conditions required are rather remote from the conditions occurring in most practical situations. At present the dissolved gas content of a fluid is seldom known and there is no available method for monitoring this on a continuous basis. The vapour pressures of mixed hydrocarbon fluids such as aircraft fuels tend to vary considerably from sample to sample depending on such factors as the origin of the crude oils and the refinery processes employed in manufacture and blending, this makes prior establishment of available NPSH in a system rather difficult. As a comparator the NPSH parameter based on average bulk fluid temperature is useful but it is difficult, if not impossible, to relate this to the processes involved in the growth of cavitation bubbles; the true NPSH is that related to conditions immediately adjacent to and within a locally cavitating region and the possibility of making the necessary measurements within the passages of a rotating turbo-machine seems remote.

8 CONCLUSIONS

The results obtained using the closed system test technique described in this Report confirm the theoretical prediction that less NPSH is required to pump water and kerosine when at elevated temperatures than when cold. They suggest that with kerosine cavitation inception occurs at the same NPSH value as with water but, in conflict with theory, the subsequent pump performance with reducing NPSH is inferior to that with water although it improves with temperature elevation. It is believed this may be due to the difference in air solubility between the two fluids leading to predominance of gaseous cavitation in kerosine and vaporous cavitation in water.

Consideration of the experimental difficulties involved in cavitation testing of multi-component hydrocarbon fluids suggests that, because of the influence of dissolved gas content and the dependence of the vapour pressure of multi-component fluids on the vapour/liquid ratio, it is doubtful whether a method of practical value to the aircraft fuel pump designer can be devised enabling the cavitation performance to be predicted from tests with other fluids.

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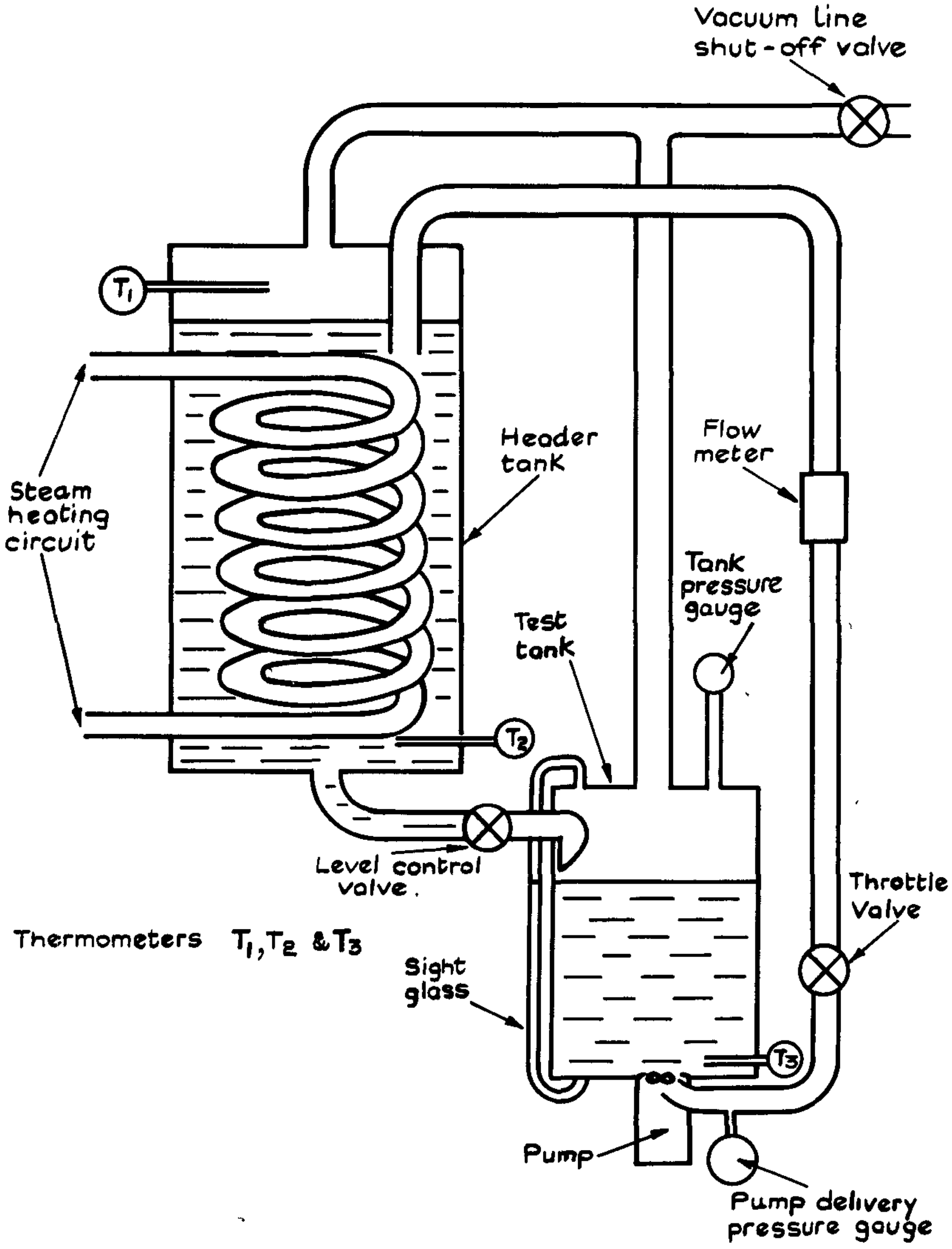

Thermometers T_1, T_2 & T_3

Not to scale.

Fig. 1 General arrangement of the test rig

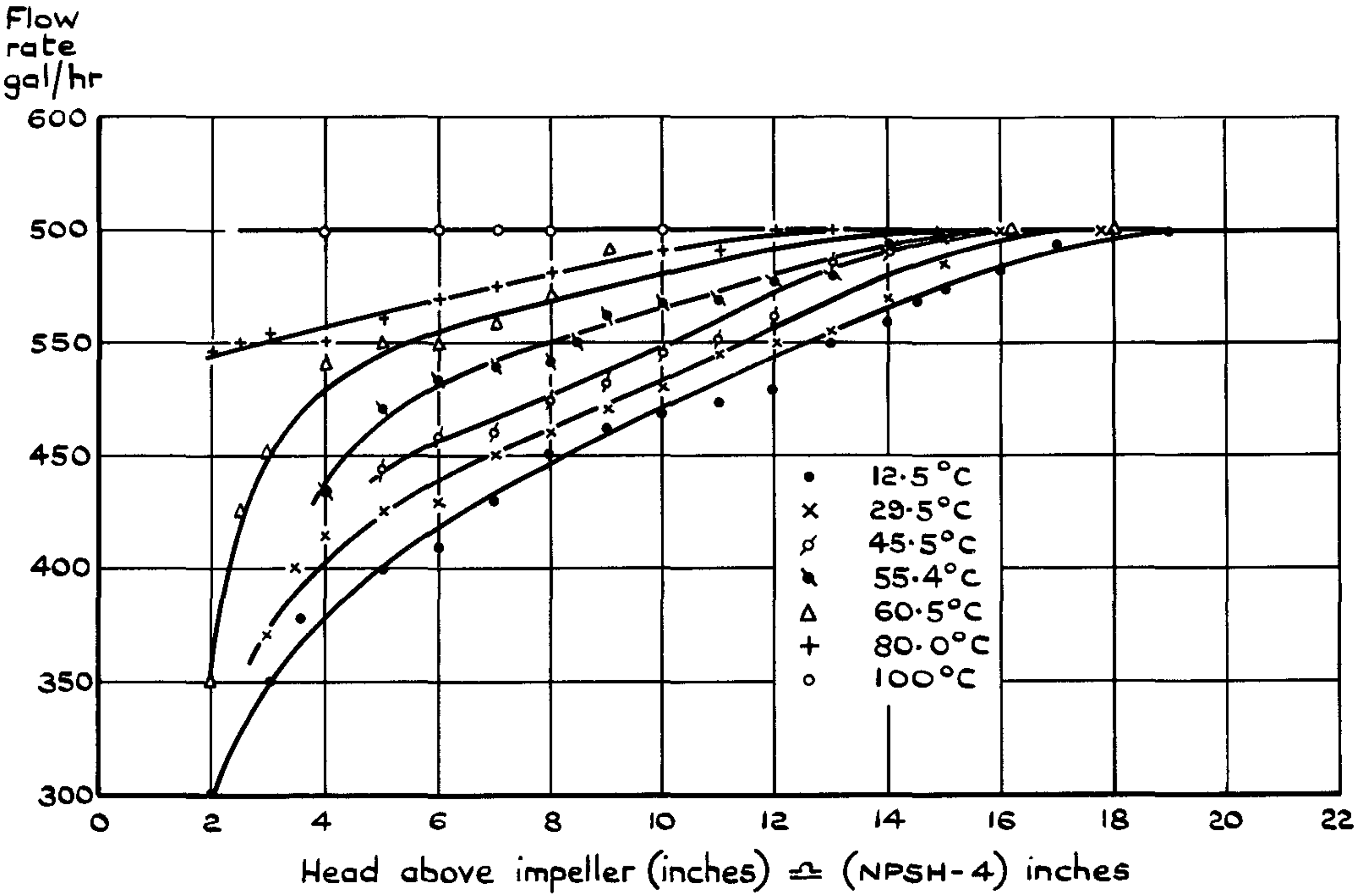

Fig. 2 Water tests–effect of reduction of NPSH on flow rate at different temperatures with constant head rise

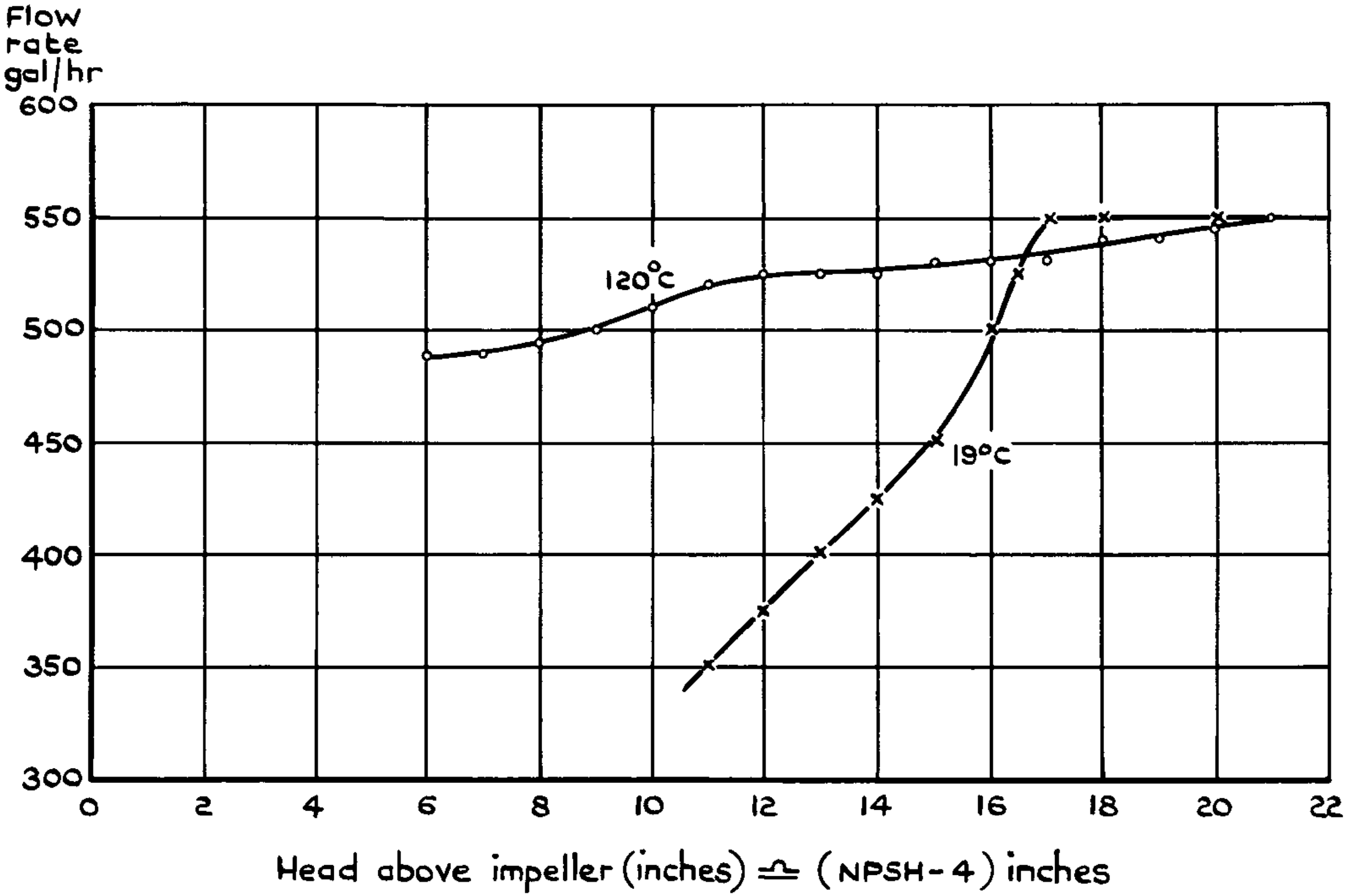

Fig. 3 Kerosine tests—effect of reduction of NPSH on flow rate at different temperatures with constant head rise

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