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Field Data Analysis of a Large Air Chamber Installation

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SUMMARY Operational field data of a large pumping installation incorporating a battery of air chambers were obtained and compared with theoretical predictions. The utilization of the RHT theory in describing the air chamber behaviour in contrast to an assumed polytropic expression, provided the best agreement between field data and analytical predictions.

Field measurements of the air temperature parameter in the air chamber revealed an extensive range of large sub-freezing temperatures. These conditions are conducive to latent heat involvements, and simplified latent heat considerations in the RHT analysis were necessary in order to provide better agreement between theory and field observations.

1 NOTATION

H^*	absolute pressure head of air mass	m
n	polytropic index	
n_o	equivalent polytropic index of a point on the H^*-V plot when referred to initial conditions.	
Q	heat outflow from air mass	J
t	time	s
T	absolute temperature of air mass	K
V	volume of air mass	m^3
γ	ratio of specific heats for air	
ρ	density of water	Kg/m^{-3}
g	gravitational constant	m/s^{-2}

2 INTRODUCTION

The water supply for a large portion of the population in the highly industrialized area around Stuttgart in Southern Germany is supplied from Lake Constance, approximately 100 km south of Stuttgart. The water is initially pumped from Lake Constance through a static lift of 312 m to nearby Sipplinger Berg where it is subjected to a sophisticated treatment process prior to being pumped further north by way of two pipelines.

The first pipeline, commissioned in 1958, is laid at ground level and crosses the European water-shed at Liptingen. The second pipeline was commissioned in 1967 and delivers water to the Stuttgart area by a more direct route employing a tunnel through the earthquake-prone Swabian Alps.

The protective devices necessary in such schemes where transients are inevitable, consist of a battery of air chambers for the first pipeline, and large flywheels on the pumps for the second pipeline.

This paper describes recent tests carried out on the section of the first pipeline which pumps water from Sipplinger Berg to the European watershed reservoir at Liptingen.

3 PIPELINE FROM SIPPLINGER BERG TO LIPTINGEN

The pipeline from Sipplinger Berg to Liptingen is approximately 22 km long, has an internal diameter of 1300 mm and rises through a static lift of approximately 64 m, as shown in Figure 1. The pipeline and its associated pumps are protected by a battery of six large air chambers, each being 7 m high and 3.5 m in diameter. In order to adequately match the variable water supply demand, four pumps are available, having maximum outputs ranging from 0.75 m^3s^{-1} to 3.14 m^3s^{-1}.

The above scheme can be compared with several pumping installations in Australia which incorporate large air chambers. The Mannum-Adelaide pipeline has three batteries of air chambers along its route, the largest having 8 chambers of 9.75 m height and 1.5 m diameter. The recently installed pumping station of the South Eastern Purification Plant in Melbourne also has a battery of 8 chambers each having a height of 9.7 m and a diameter of 2.3 m.

4 RECORDING OF AIR CHAMBER DATA

The main parameters involved in the behaviour of an air chamber are the absolute pressure head (H^*), the volume (V) and the absolute temperature (T) of the enclosed mass of air. The sophisticated instrumentation used to record these parameters of the air chambers at Sipplinger Berg is described elsewhere (Graze et al, 1976). The anologue computer employed on site for these measurements was used to record the product of H^*V/T. Since this term is a function of the perfect gas law, and since the enclosed mass of air can be considered to closely represent a perfect gas, the constancy of this term is a guide to the recording accuracy of the three independently recorded parameters. It was encouraging to note, that during the numerous tests at Sipplinger Berg this product, H^*V/T, remained essentially constant for each test, thus giving substance to the accuracy of the recorded data.

In each test at Sipplinger Berg the transients caused by pump failure were simulated by simply switching off the pumps. A variety of test results was obtained by establishing different steady state conditions before the specific pump in operation was switched off. For the purpose of this paper, only the data from Test 8 will be discussed.

5 FIELD MEASUREMENTS

Test 8 involved the running of the second smallest pump, at a steady state discharge of 1.40 m^3s^{-1} and with three air chambers connected. Before switching off the pump, each air chamber contained 26.7 m^3 of air.

The following information was recorded :-

(i) On an X-Y plotter, the absolute pressure head and the volume of the enclosed mass of air of a single air chamber were plotted against each other on a linear scale as shown in Figure 2. Only the first two cycles have been reproduced for clarity.

(ii) On a UV recorder, the three relevant parameters of the enclosed mass of air of a single air chamber were recorded against time as reproduced in Figure 3, and identified with the subscript "EXP". Only the first cycle has been shown.

6 THEORETICAL ANALYSES

The transient behaviour has been theoretically analysed using the Method of Characteristics, incorporating the appropriate boundary conditions at the upper reservoir and at the air chambers. The constant head outlet at the upper reservoir has been considered by allowing for a variable boundary condition dependent on the direction of flow. The lower boundary condition has been allowed for by considering the transient behaviour of the enclosed air mass. The analyses assume instantaneous closure of the check valve following pump failure. The calculated results for the first cycle of Test 8 are shown in Figure 3 depicting the time history of the absolute pressure head, the volume and the absolute temperature. The theoretical data are identified with the subscript "RHT".

6.1 Polytropic Equation, H^*V^n = constant

The assumption generally employed to describe the behaviour of an air chamber is to apply the polytropic equation with various constant values of n. However, in several recent publications (Graze, 1968, 1971, 1972), it has been demonstrated that this assumption is fundamentally wrong.

The utilization of the pneumatic energy of the air chamber is not only confined to pumping installations but is becoming accepted practice in hydro-electric schemes (Svee, 1972; Graze et al, 1976, Brekke, 1974). In the latter case a rational understanding of the air chamber is essential, especially where governing over an extended period of time is involved. It is therefore considered that the use of the polytropic equation should be replaced by a rational approach.

6.2 The RHT Equation

A concept based on the rational heat transfer (RHT) of the enclosed air mass of the system has been described elsewhere (Graze, 1968, 1971), and is summarised by the differential equation (1),

$$\frac{dH^*}{dt} = -\gamma \frac{H^*}{V} \frac{dV}{dt} - \frac{(\gamma-1)}{\rho g V} \frac{dQ}{dt} \qquad (1)$$

where the symbols are defined under 'Notation'.

The virtue of the RHT equation is that the $^{dQ}/_{dt}$ term can accommodate all forms of energy rates flowing in or out of the air mass.

6.3 Rate of Heat Outflow

The substitution of the correct form of the $^{dQ}/_{dt}$ term in the RHT equation has been the subject of research in recent years.

In the past, the assumption of free and/or forced convection has provided satisfactory results, especially when the temperature of the air remained between the freezing and boiling points. This is generally the case where the initial transient involves the compression of the air volume.

However, in the case of pump stoppages, the initial transient generally introduces an expansion of the air volume which can readily lead to sub-freezing temperatures of the air. Thus mention has been made of accommodating latent heat in the $^{dQ}/_{dt}$ term. Latent heat transfers occur as a result of ice formation, when the air temperature falls below the freezing point for an extended period of time. The latter case exists in Test 8, as evidenced by the field data of Figure 3, where the air temperature in the first cycle remains approximately two minutes below freezing point and reaches a minimum of -30^{0}C during this period of time.

It is therefore considered that latent heat terms can no longer be ignored, especially for installations of this magnitude.

7 DISCUSSION OF RESULTS

Considering the magnitudes of the parameters involved, the agreement between the theoretical data and the field observations is seen to be quite satisfactory. Although some mismatch of the extreme values still exists, the main discrepancy is related to the periods rather than the amplitudes.

For the RHT analysis shown in Figure 2 and Figure 3, a heat transfer rate using free convection was adopted. The equations for this are detailed elsewhere (Graze, 1968, 1972; Graze et al, 1976).

(For comparison purposes, the extreme values of the pressure head and the volume of the air mass resulting from polytropic analyses using n = 1.4 and n = 1.2 are included in Figure 2).

7.1 Latent Heats

There are two forms of latent heat that need to be considered in the present analyses - that which occurs during condensation and that which occurs during freezing and vice versa.

7.1.1 Condensation

As the air temperature drops following the initiation of the transients, the air becomes saturated with water vapour. Any further drop in temperature tends to release latent heat to the surroundings and causes the formation of water droplets. In theory this process is complete when the air temperature reaches the freezing point. From this point on in time the air may be considered as 'dry', even during subsequent expansion, since the air has no time to re-saturate.

Since the amount of water vapour present can readily be calculated, there is no difficulty in allowing for this form of latent heat. However, the theoretical analyses for the inclusion of this form of latent heat reveal only a slight improvement on the theoretical predictions plotted in Figure 3. The main difference in the analyses depicts the minimum value of the air temperature occurring earlier, thus emphasizing the occurrence of 'phase difference' as is also evident from the field data. Further consideration of the inclusion of this form of latent heat indicates that its release is time dependent. This is to be expected since the formation of the water droplets is not instantaneous but a function of time depending on the size of the droplets. Allowance was therefore made in the theoretical analysis to release the amount of latent heat available in the water vapour over various time periods, some extending well into the sub-freezing range. Once again the differences from the initial analyses were marginal except that the above-mentioned phase difference was emphasised even further.

From the above it can be concluded that for the hydraulic system considered in this paper, the energy contained in the long moving column of water dominates over the available amount of latent heat released from the water vapour present.

7.1.2 Freezing

From the previous considerations it becomes obvious that large amounts of additional energy are necessary in the dQ/dt term in order to match the theoretical data with the field data. This is especially so with respect to the time parameter. The source for this additional energy is available from the large amount of water present in the air chamber which is subjected to sub-freezing temperatures for an extended period of time as shown in Figure 3. The current state of the art does not permit to predict the heat rate or the amount of water which freezes under these circumstances in order that it can be rationally included in the dQ/dt term.

However, several arbitrary but feasible latent heat rates for ice formation were tested in the theoretical RHT analysis in order to check on the trend postulated above. From these it was obvious that this quantity of latent heat can have a considerable effect on the transients and consequently warrants further investigation.

The occurrence of the formation of ice is further supported by the recorded air temperature versus time plot, as shown in Figure 3. The temperature dropped to freezing in the first 10 seconds of the transients and remained below freezing for a further two minutes. During this time, ice formation as discussed above, would occur, and any minute water droplets on the temperature recording wire would then also freeze. The recorded temperature trace near the 130 second mark shows that as the temperature reaches the freezing point, the wire temperature remained at the freezing point for approximately six seconds before rejoining the overall temperature gradient a few seconds later. This behaviour implies that ice had formed on the wire and latent heat had to be absorbed for melting and evaporation before the wire temperature returned to the overall air temperature gradient.

If the wire is subjected to a thin layer of ice, the temperature record would tend to lag behind the true air temperature. Consequently, the recorded temperature shown in Figure 3, probably indicates slightly higher values than the actual air temperature. This would tend to reduce the discrepancy with the calculated RHT values.

Finally it is of interest that visual inspection of the interior lining of the air chambers at Sipplinger Berg has revealed a curious form of corrosion. It appears possible that the repetitive cycles of large temperature ranges and large temperature gradients, (i.e. 75^0C temperature change within a period of two minutes for Test 8), together with the occurrence of freezing and thawing, could be partially or even wholly responsible for this corrosion.

7.2 Phase Differences

The existence of phase differences between the extreme values of pressure head, volume and temperature is a matter of fact as discussed elsewhere (Graze, 1971).

When large quantities of latent heat are involved, these phase differences are highlighted as evidenced by both theory and field data. In Figure 3 it can be seen that for the Sipplinger Berg Test 8, the minimum temperature leads the minimum pressure by approximately twelve seconds, and the maximum volume occurs approximately four seconds later. It should be noted that this trend can not be modelled with a polytropic analysis. In fact, any polytropic analysis would show all three parameters to be in phase.

7.3 Polytropic Index, n_o

The apparent polytropic index obtained when any compatible values of pressure head and volume are referred back to their corresponding initial steady state values is termed n_o. The variation of n_o during the transients can be appreciated from Figure 2.

At the start of the transients, n_o is 1.4. It then goes through various values including large positive and negative numbers, before finally reaching equilibrium conditions with $n_o = 1.0$. The errors resulting from the assumption of a constant value of n in the polytropic equation are obvious.

8 CONCLUSIONS

i) The RHT theory has previously been found to provide very good results when latent heat considerations were not necessary (Graze 1968). Although the results without latent heat considered are within reasonable accuracy even when sub-freezing temperatures are involved, the RHT theory provides a facility to improve the theoretical analysis by incorporating the latent heat flows in the dQ/dt term in Equation (1). This facility is not provided by a polytropic analysis.

ii) The latent heat involvement of the gas/liquid transformation of the water is generally dwarfed in air-chamber installations by the kinetic energy of the moving column of water in the pipeline. However, the latent heat involvement of the liquid/solid transformation of the water appears to markedly affect the overall

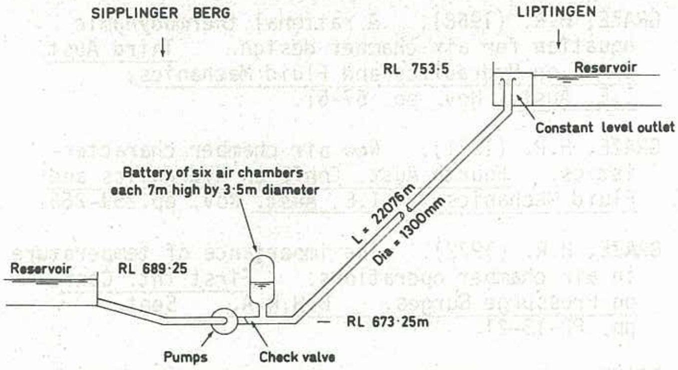
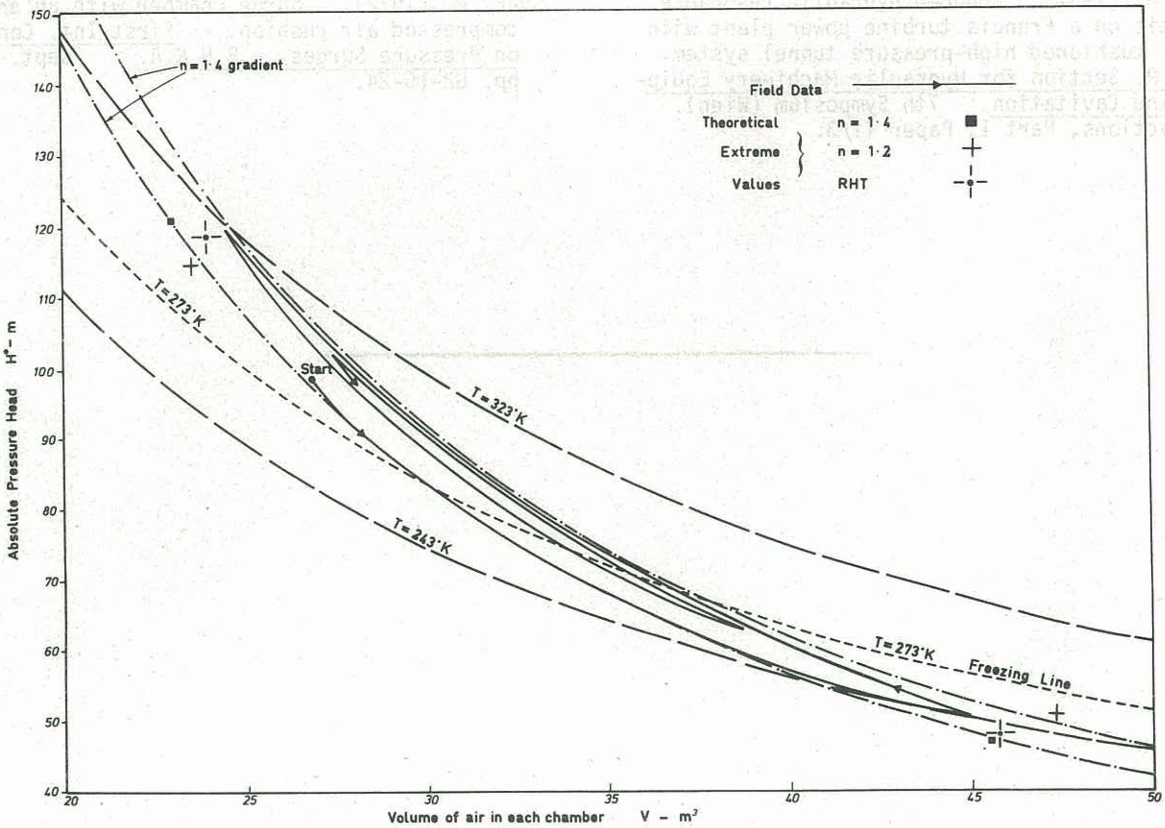


Figure 1 Air chamber installation at Sipplinger Berg

Figure 2 Pressure head versus air volume for run 8- Sipplinger Berg



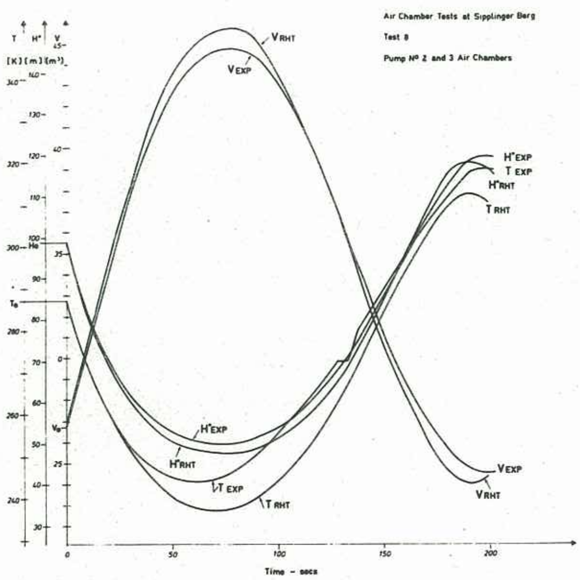


Figure 3 Experimental and theoretical transients for head, volume and temperature within single air chamber

dynamics of the hydraulic system, and further research in this field is necessary.

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