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NEW AIR CHAMBER CHARACTERISTICS

by

H.R. Graze, B.C.E., Ph.D., M.I.E. Aust.*

SUMMARY

A few years ago (1967), the author proposed a new approach to describe the air behaviour in an air chamber. This approach, which formulated a new equation based on the rational heat transfer (RHT) of the air chamber system and which is intended to replace the only other method so far utilized in hydraulic systems, i.e. the empirical polytropic equation with its inherent fundamentally wrong application, results in new rational air chamber characteristics which cannot be postulated with the polytropic equation method.

In consequence, phase differences between the extremes of the air properties (pressure, volume, etc.) during the transient history of the air volume exist. More importantly, a significant new form of attenuation besides the presently accepted hydraulic concept, is present. Furthermore, the temperature of the 'air' which is generally a neglected parameter in these systems becomes an important variable which can lead to extremes of pressure not previously predictable.

* H.R. Graze, Senior Lecturer in Civil Engineering, University of Melbourne.

LIST OF SYMBOLS

n	Polytropic index	
p	Absolute pressure	Nm^{-2} , m
Q	Heat outflow	J
t	Time	s
T	Absolute temperature	K
ΔT	Alg. temperature difference between air and wall of chamber	K
V	Volume	m^3
γ	Ratio of specific heats	

1. INTRODUCTION

The behaviour of air chambers incorporated in hydraulic systems is generally assumed to be defined by the empirical polytropic equation, pV^n = constant, wherein the polytropic index, n , may be a fixed value varying from 1.0 to 1.4 (i.e. isothermal to adiabatic behaviour). A literature survey reveals that in the past a strong affinity towards the isothermal assumption existed especially with European researchers, while the tendency today (1971) generally favours an intermediate value of $n = 1.2$ (1), (2), (3).

However it can be shown (4), that especially due to the large heat sink of the air chamber itself, the application of the polytropic relationship in these hydraulic systems is fundamentally wrong and no longer suitable in an era where rationalization and a trend towards greater accuracy in all disciplines are of prime importance. If the time history of the air is to be defined by an equation similar to the polytropic one and if the analysis is to remain rational, then n must be a variable with time, i.e. $pV^{n(t)}$ = constant - a function which cannot be predetermined (5).

In place of the polytropic relationship which due to its simplicity served a very useful purpose in a period when computational techniques were meagre, an equation based on the rational heat transfer (RHT) of the air chamber system was proposed (1), (4). This rational equation which can be readily manipulated with the present day use of computers, in general provided far superior predictions of the transient results. An analysis of this equation reveals new air chamber characteristics.

2. THE RHT PROCESS

The RHT process essentially consists of a thermodynamic differential equation which together with the two principles of continuity and momentum can readily be solved with the application of computational techniques.

This thermodynamic equation is given below (4).

$$\frac{dp}{dt} = -\gamma \frac{p}{V}\frac{dV}{dt} - \frac{(\gamma-1)}{V}\frac{dQ}{dt} \qquad (1)$$

where
p = absolute pressure of the air volume,
V = volume of air,
γ = ratio of specific heats,
$\frac{dQ}{dt}$ = rate of heat outflow, and
t = time.

The difficulty with the above equation lies with the correct substitution of the rate of heat outflow term, dQ/dt , (1). Although it can be shown (4), that to the first order of approximation this term mainly incorporates thermal convection between the 'air' and the inside wall of the air chamber only, a literature survey indicates that ".... such a general problem can only be approached by approximate analytical analysis" (6).

Fortunately it has been observed that the term in question, although a very vital parameter, is of an insensitive nature and thus only the order of magnitude of the term is necessary for good results. It has been found that the assumption of free convection, as given below, provided very satisfactory comparisons between theory and laboratory results (4).

$$\frac{dQ}{dt} \mid \text{unit area} = 0.19 \mid \Delta T \mid ^{1/3} . \Delta T \qquad (2)$$

where ΔT = algebraic temperature difference between the air and wall of chamber - the former temperature T being readily obtained from the equation of state.

This insensitive nature postulates that the application of the RHT process together with Eq. (2), should be valid for both horizontally as well as vertically placed air chambers.

3. PHASE DIFFERENCES

The term 'phase difference' in this context designates the time interval between the corresponding opposite extremes of pressure and volume (and temperature) of the air volume in the particular half-period of transient oscillation under consideration, Fig. 1. Thus if the gradient, dp/dV , on a $p - V$ plot is positive in the stated region, phase differences must exist.

For the polytropic process, dp/dV is always negative, i.e. the extremes always coincide and no phase differences are possible, Fig. 1.

If the ratio of specific heats, γ , for air is assumed to be 1.4, Eq. (1) of the RHT process can be rewritten so that for a positive value of the gradient, dp/dV, the following conditions must be necessary.

Rate of heat outflow > 3.5 x Rate of work input* (3a)
or Rate of heat inflow > 3.5 x Rate of work output (3b)

It can readily be appreciated that, except for the special case of isothermal specifications, condition (3a) exists in the stated regions, i.e. when the rate of work input is zero the rate of heat outflow has a finite value, and that phase differences therefore must always be present. Similarly for condition (3b).

As an example, for the particular laboratory data stated and analysed in Ref. (4) for Run$|^{AB}$, the air behaviour as depicted in Fig. 1 is reproduced to an exaggerated scale in the inset of Fig. 2, which illustrates the theoretical phase difference

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* Although this also applies to polytropic processes, the particular specification of a polytropic process makes the heat outflow zero at the same instant as the work input is zero, despite the fact that at that instant a temperature difference, ΔT, exists (4).

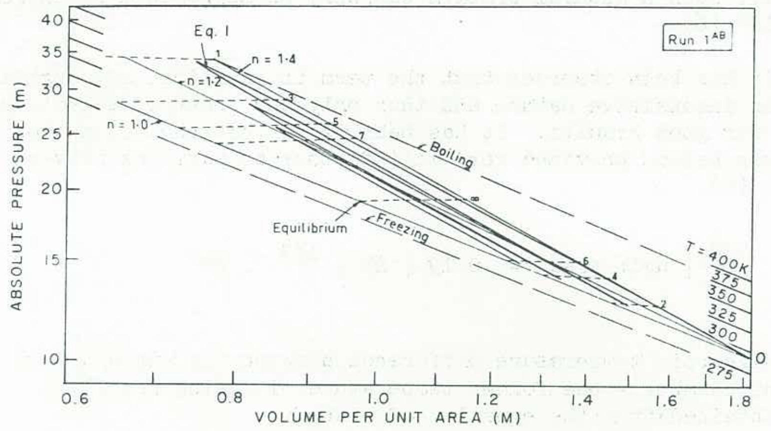

FIG.1 COMPARATIVE THEORETICAL p-V-T VALUES

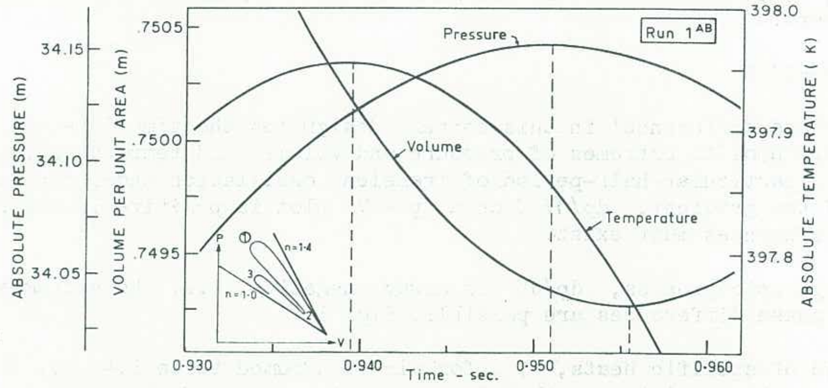

FIG. 2 THEORETICAL PHASE DIFFERENCE AT FIRST EXTREME

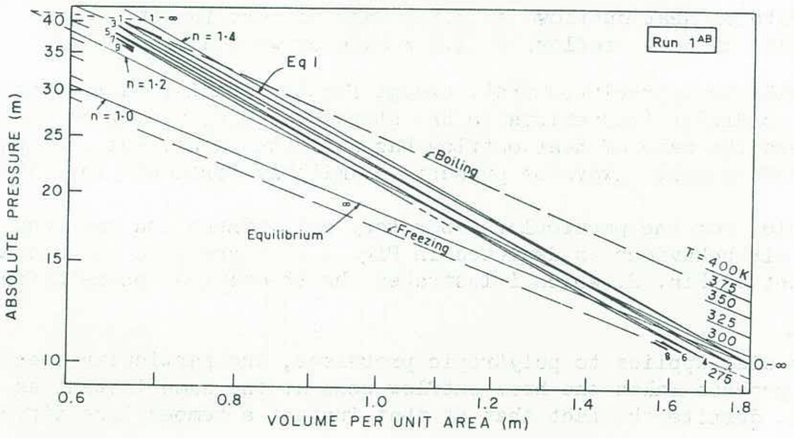

FIG.3 COMPARATIVE THEORETICAL p-V-T VALUES WITHOUT HYDRAULIC LOSSES

at the first extreme, 1.

Longer phase differences can obviously be expected for prototype installations.

4. NEW CONCEPT OF ATTENUATION

According to the present day literature, the only type of energy loss allowed for in hydraulic systems has been of a hydraulic nature. Thus in an installation incorporating an air chamber whose air behaviour is specified by a polytropic process, the variables involved would show no attenuation after an initial disturbance if all the hydraulic losses such as fluid friction, orifice loss, etc. were to be neglected.. In the particular case depicted in Fig. 3, this situation is represented by the non-attenuating performance illustrated by the 'one-line' characteristic between 0-∞ and 1-∞ for the appropriate value of n . Even if it were possible to have no hydraulic losses, the behaviour indicated would still not be compatible with the actual performance of an air chamber in which thermodynamic energy transfer takes place, i.e. the polytropic process specifies an artificial net balance between work done and heat outflow such that at any stage the work done is only a function of the initial and final air volume and is independent of the intermediate transient history - similarly for the net heat outflow (1).

As is to be expected from the previous section, this non-realistic behaviour with its 'one-line' characteristic does not apply to the RHT process. A similar analysis using the same data as previously but neglecting hydraulic losses and employing the RHT process leads to the results depicted in Fig. 3. In this diagram the change from an initial 'adiabatic' behaviour to an 'isothermal' one with respect to the initial conditions and the consequent attenuation is clearly demonstrated.

For the stated example, the attenuation of the volume per unit area between the initial value and the first peak in Fig. 1 is 0.30 m, while in Fig. 3 it is approximately 0.075 m. Thus in this particular case, this new thermodynamic concept of attenuation accounts for approximately 25% of the damping.

5. TEMPERATURE

A literature survey all too clearly reveals the neglect that is bestowed on the temperature parameter in air chamber analyses. There are isolated cases where the temperature has been considered - however for different purposes than understanding the fundamental behaviour of these chambers. Thus Patterson et al (7) were concerned with the metallurgical aspects of the chamber itself while Lang (8) considered the effect of air temperature on the stability of the hydraulic system.

The temperature, besides affecting the system performance as discussed above, is furthermore directly responsible for calling forth extra amounts of energy which may lead to extremes of pressure not previously predictable in the polytropic process.

In Fig. 1, temperature scales have been superimposed and it should be noted that the temperature of the 'air' volume under consideration lies well within the sketched 'boiling' and 'freezing' lines for water. It can readily be appreciated that if the volume had been initially expanded, as tends to be the more general case in an actual air chamber installation, rather than compressed as in Fig. 1, the air temperature would tend to fall below the freezing line and consequently call forth extra amounts of energy in the form of latent heat. This 'booster' energy could send the pressure well below the pressures predictable by any of the polytropic processes and is considered to be the cause for exactly such experimental results obtained by the author.*

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* A paper is being prepared.

A similar situation would exist with temperatures exceeding the 'boiling' line thus emphasizing the importance of the operating air temperature of the chamber.

A literature survey has unfortunately failed to uncover sufficient experimental field data for a comparison with a RHT analysis. Thus the author is all the more grateful that he has been able to visit an organization (9) which has realized the importance of prototype data and has commenced closely controlled field studies on one of its major water supply routes from Lake Constance to Stuttgart (180 km) as part of an intensive air chamber investigation programme. Temperature as well as the pressure and volume parameters are being measured and preliminary analyses have shown that there appears to be a 'temperature pause' as the temperature reaches the freezing point of water.

The importance of the temperature is thus further highlighted by its influence on the composition of the 'air' in the chamber, especially with respect to the presence of water vapour. Consequently, when further rationalization has reached the stage where these additional, or any other, heat energy terms can be adequately specified, the RHT process using Eq. (1) can readily accommodate these considerations.

Finally it should be observed that the ranges of temperature reached in air chambers can be very large and that it is interesting to note that even considerations have been given to utilize these temperature variations for commercial usage.

6. CONCLUSIONS

The application of the rational RHT process to air chamber analyses has revealed new air chamber characteristics which may prove important under certain conditions but which cannot be created with the polytropic equation method.

Any further development regarding a rationalized understanding of air chamber behaviour, such as the inclusion of latent heat postulations, will have to follow an approach similar to that depicted by Eq. (1) in which the heat transfer term may absorb any desired thermodynamic considerations.

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