FIFTH AUSTRALASIAN CONFERENCE

on

HYDRAULICS AND FLUID MECHANICS

at

University of Canterbury, Christchurch, New Zealand

1974 December 9 to December 13

NEW DESIGN CHARTS FOR AIR CHAMBERS

by

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SUMMARY

A preliminary design for an air chamber installation generally bases its initial air chamber dimensions on the data provided two decades ago by Evans and Crawford. Besides using the empirical polytropic equation with an index of 1.2, they also assumed in their analysis that the total head losses in the hydraulic system were concentrated across the orifice situated at the air chamber.

The present paper does not make this assumption but distributes the losses between the orifice and the pipeline. As a result of this distribution, the maximum upsurges in the Evans and Crawford charts tend to be markedly reduced, while the maximum downsurges are slightly increased.

The new set of charts which make due allowance for hydraulic friction along the pipeline, is an improvement on the well known Evans and Crawford air chamber design charts.

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LIST OF SYMBOLS

A = cross-sectional area of pipeline, in m^2
a = velocity of propagation of water hammer waves, in m/s
C = volume of air in air chamber, in m^3
g = acceleration due to gravity, in m/s^2
H^* = absolute pressure head in the air in chamber, in m
K = coefficient expressing the total head loss such that KH^*_o is the total head loss for flow AV_o into chamber
$K3$ = component due to pipeline friction
$K4$ = component due to orifice loss
L = length of pump discharge pipeline, in m
n = polytropic index
V = velocity of flow in pipeline, in m/s
ρ^* = pipeline characteristic
σ^* = air chamber characteristic
Subscript 'o' indicates steady state conditions prior to power failure
$H^*_{max} - H_o$ = Maximum Upsurge
$H^*_o - H^*_{min}$ = Maximum Downsurge

INTRODUCTION

The application of air chambers as protection devices in hydraulic systems has in recent times increased considerably (1-5). Although the usage of these chambers is generally associated with pumping installations, the concept of adopting this stored energy in the form of an enclosed air volume, is now also being applied to hydro-electric installations (2,3). Thus in Norway in a revolutionary trend, huge caverns have been excavated in the interior of mountains to duplicate the functions normally required from the conventional surge tank installation. Consequently, besides the practical problems (for example, leakage of air through the mountain rock), a proper appreciation of the dynamic behaviour of these enclosed air volumes, forms an important feature in the overall performance of such hydraulic systems.

In the past, the performance of these chambers depended on the assumption that the dynamic behaviour of the enclosed air volumes could be adequately represented by the empirical polytropic equation, $H^* C^n$ = constant. A 'fast' process for air was associated with $n = 1.4$, while a 'slow' one assumed $n = 1.0$. However, since it is generally difficult to designate these processes as either 'fast' or 'slow', especially since they also depend to a large extent on the mass of compressed air, the trend for many years now has been to describe the thermodynamic behaviour of the air by the adoption of the intermediate value of $n = 1.2$ in the polytropic equation.

The assumption of $n = 1.2$ was used in the generally accepted air chamber design charts of Evans and Crawford (6) which depict both the maximum upsurge and the maximum downsurge against a dimensionless number, $2\rho^*\sigma^*$, incorporating the major parameters of an air chamber installation in a pumping system. The charts based on the sudden power interruption to the pump motor, have been in use for the past two decades and have served a very useful purpose in estimating the approximate maximum surges for a particular installation subject to power failure.

Some time ago (1967), attention was drawn to the fact that the adoption of the polytropic equation for an air chamber installation was, with respect to the thermodynamic behaviour of the system, fundamentally wrong in principle and that large errors could readily result with the wrong choice of the polytropic exponent 'n' - the error being largest for the air volume considerations. In response, a new theory termed the Rational Heat Transfer (RHT) theory - was evolved (7,8) which allowed for a rational heat transfer into and out of the enclosed gaseous volume. Due to the generality of this RHT theory, all forms of heat transfer can be incorporated, including latent heats which are generally to be expected in the first downsurge on power failure in a pumping installation.

The success of the RHT theory depends on substituting an adequate heat transfer term in the rational equation. The adoption of a free convection heat transfer term has so far indicated encouraging results, provided the latent heat effects were negligible (8,9). Thus the present Evans and Crawford air chamber charts (6,10) could readily be updated to allow for a more acceptable rational air chamber behaviour. A comparison between this 'rational' theory and the 'empirical' theory, in fact indicates that for some values of the dimensionless air chamber number, the differences are small with respect to the magnitude only of the maximum surge, but can be substantial for other practical air chamber numbers. However, the predicted differences in the volume estimates are considerably greater.

A complete new set of rational air chamber charts would be extensive since new parameters, such as temperature (9), would have to be included. Furthermore, latent heat considerations should also feature, if possible, in any new up-to-date charts. A further important consideration, which was not included in the Evans and Crawford analysis due to a lack of computer facility, has to be incorporated in any new charts. This extra parameter highlights the importance of the distribution of the hydraulic loss into its throttle (orifice) loss components and pipeline (friction) loss component (4,11).

Since the present format of this paper is too short to include all of the above and since the latent heat terms have become part of a sponsored research project, it appears very deisrable to only highlight in this paper the effect of the distribution of these hydraulic loss components.

The new charts, resulting from the hydraulic loss distribution, should thus prove to be a better base from which to estimate the air chamber sizes for preliminary designs, while the RHT theory in its present form (9) should still be used for an analysis of the dynamic behaviour itself.

THEORY

The design charts of Evans and Crawford (6) were based on several assumptions, the major ones being summarized below:

a) the check valve on discharge side of pump closes immediately on power failure,
b) the chamber is situated near the pump,
c) the pressure head-volume relationship for the air in the chamber may be expressed as $H^* C^{1.2}$ = constant, and
d) the ratio of the total head loss for the same flow into and from the chamber is 2.5:1.

In order to make the comparison realistic, these assumptions were also adopted in the present paper.

Although it has been shown (7,11) that the elasticity of the water and the conduit play a minor role in the analysis, Evans and Crawford decided to employ the rigorous water hammer theory to predict the maximum upsurge as well as the maximum downsurge in the air chamber. They based their analysis on the graphical method of R. W. Angus (12). Their resulting charts incorporated the following dimensionless parameters (Fig. 1).

$$\text{Pipeline Characteristic} \qquad \rho^* = \frac{aV_o}{2gH_o^*}$$

$$\text{Air Chamber Characteristic} \qquad \sigma^* = \frac{2g\ C_o\ H_o^*}{AL\ V_o^2}$$

$$\text{Loss Characteristic} \qquad K = \frac{\text{Total Head Loss for Flow } AV_o \text{ into Chamber}}{H_o^*}$$

The analysis implied that the total head loss was concentrated at the orifice with no hydraulic losses in the pipeline. This, together with assumption (a), introduced an abrupt wave into the computations. However, the assumption that all the hydraulic losses are concentrated at the orifice is unrealistic, and with the present day availability of computer techniques, is no longer justified.

For the new charts included in this paper, the total head loss was divided into its various throttle loss and pipeline loss components so that $K = K3 + K4$

where K3 = component due to pipeline friction, and
K4 = component due to orifice loss.

The present analysis furthermore used the method of characteristics (13) for the water hammer phenomenon in the pipeline.

THE CHARTS

The charts, Fig. 2, for comparison purposes, have been plotted in a similar manner to those of Evans and Crawford, with the same values of K, i.e. 0, 0.3, 0.5 and 0.7. Furthermore, the charts also depict the maximum surges when:

i) all the losses are concentrated at the orifice, i.e. K3 = 0,
ii) all the losses are distributed in the pipeline, i.e. K4 = 0,
iii) the losses are equally distributed for inflow, i.e. K3 = K4.

The condition of K3 = 0, represents the situation analysed by Evans and Crawford and it is a credit to their graphical technique that their results differ very little from the computer data represented in Fig. 2(a), (b), (g) and (j).

The new charts clearly show the conservative nature of the Evans and Crawford data for maximum upsurge. As K3 increases, the maximum upsurge is expected to decrease while maximum downsurge increases. This is verified in the charts, but the reduction of the upsurge is far greater than the increase in the downsurge. The effect of the various ratios of K3 and K4 for K = 0.3 and ρ^* = 1 and 4, is dramatically depicted in Fig. 2(e) and (f) respectively.

For K = 0.3 the attached charts incorporate, as have been done with the Evans and Crawford data, the maximum surges at the mid length point as well as in the chamber. However, for clarity, the charts for K = 0.5 and 0.7 only depict the maximum surges in the chamber, and it should be observed, that for these cases there is practically no upsurge when K4 = 0.

The charts, for example, serve a useful purpose where the upsurge in the pipeline is to be minimized (i.e. weak pipeline material, for example, plastic) and the size of the chamber is of no great consequence. Similarly, the charts are useful where the friction in the pipeline is very high.

Finally, it should be observed that the charts have been drawn without any 'practical limit' on their dimensionless numbers in mind.

CONCLUSION

The attached charts emphasize the importance of pipeline friction - a parameter which will have to be considered in any future air chamber charts, and one which has a marked effect on the maximum upsurges.

The charts are an improvement on the Evans and Crawford charts and may be used for preliminary design work. However, a final analysis, especially with respect to the volume changes will still have to be made at this stage for the dynamic behaviour of the system.

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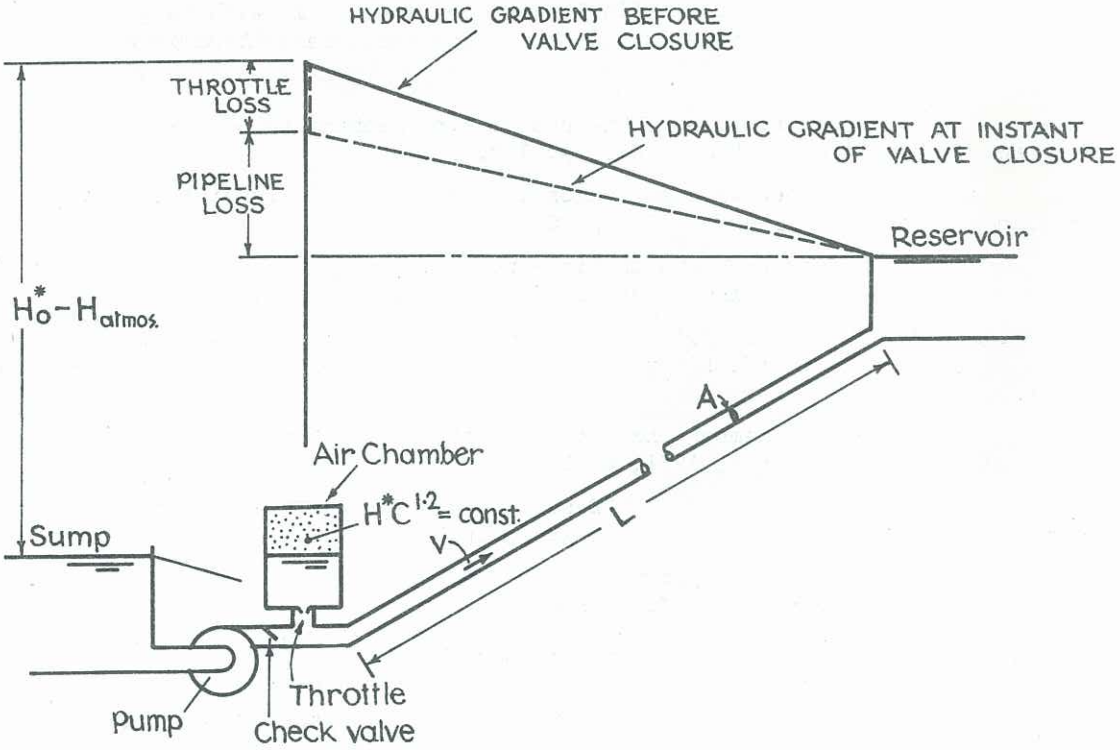


FIG. 1. SCHEMATIC AIR CHAMBER INSTALLATION

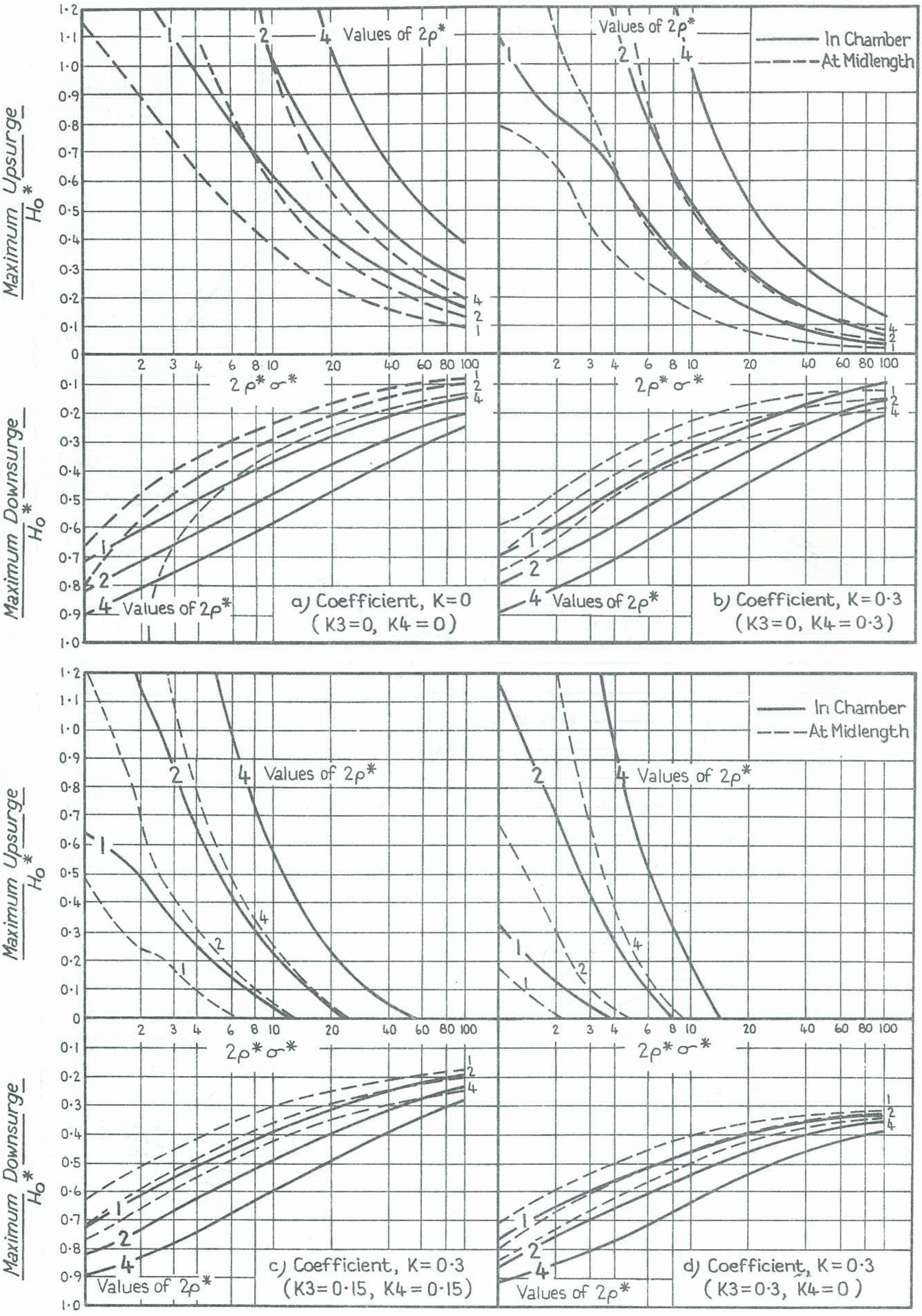
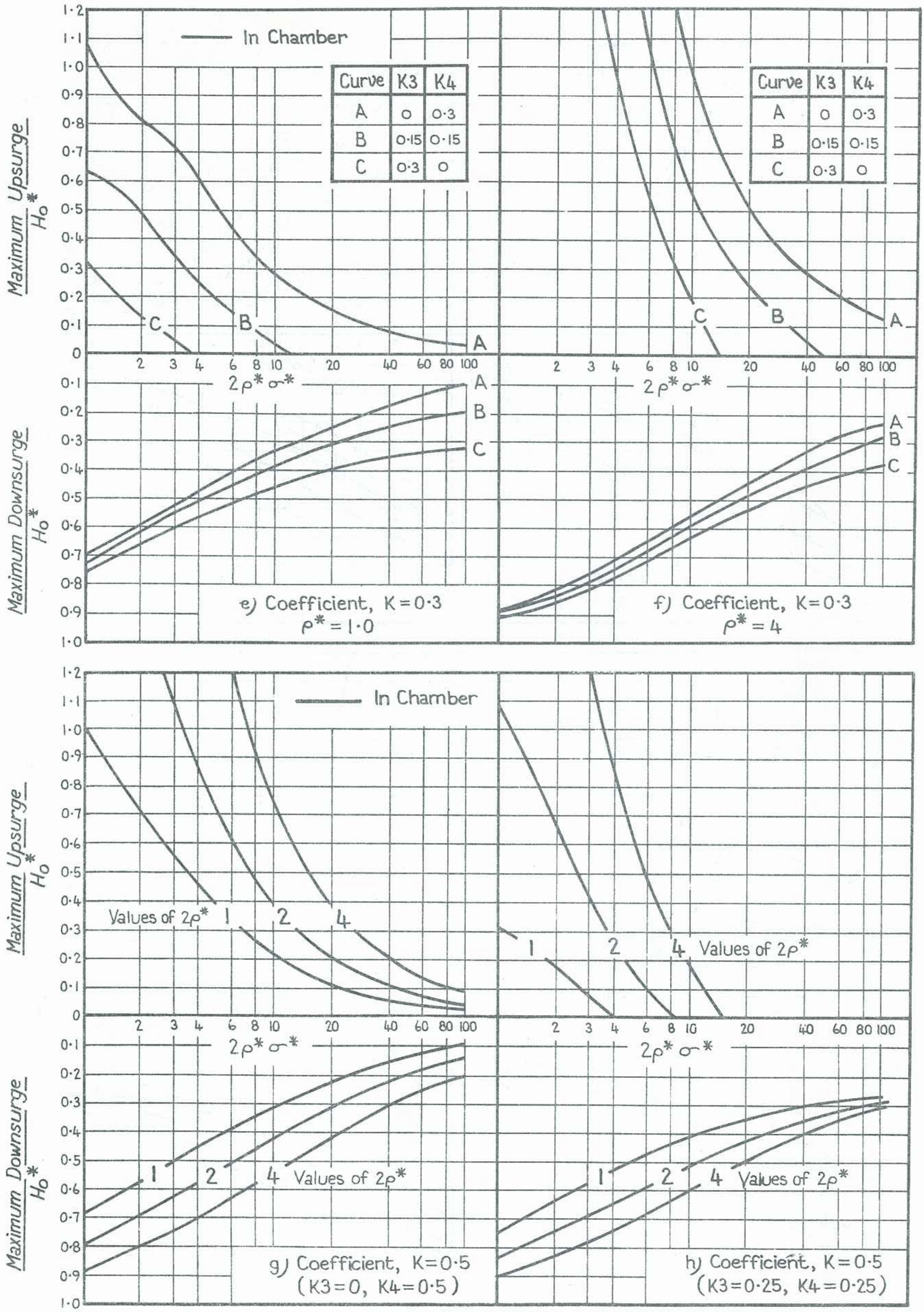


FIG 2. MAXIMUM SURGES FOR A 'THROTTLED' AIR CHAMBER



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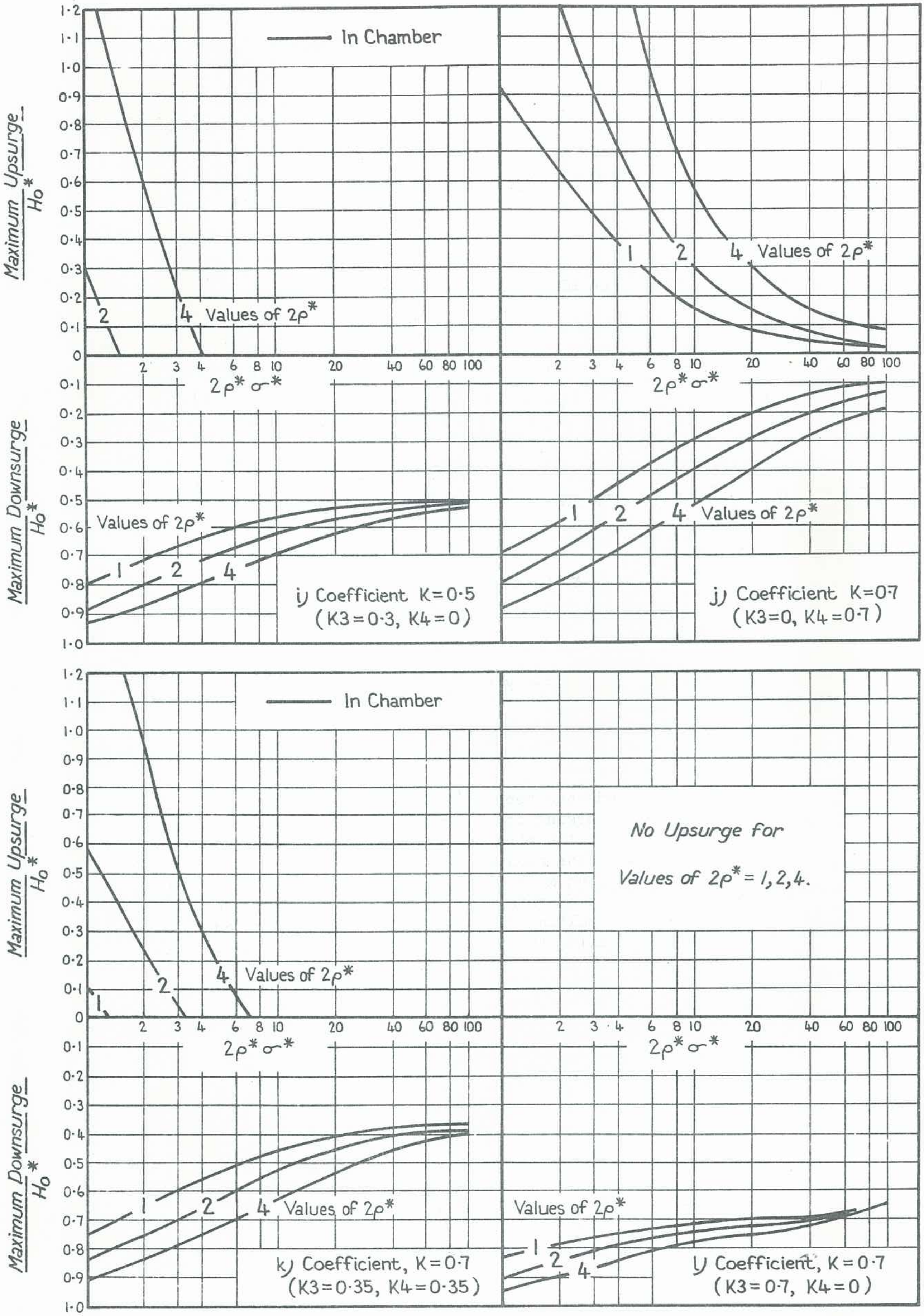

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