

Theoretical and experimental investigation of air-regulated siphons

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Dr D. A. Ervine, Department of Civil Engineering, The University, Glasgow
The Paper is one of the most useful and comprehensive on air-regulated siphons, to date. I am interested in the application of the irrotational flow equation (1) combined with the energy equation (2), to predict the head/discharge curve of an air-regulated siphon, and the air pocket pressure and head over the crest during sub-atmospheric weir flow. It is encouraging to see a close relationship between theory and experiment for Head's siphon at a scale of 1/6.5. Do the Authors envisage this type of approach for predicting the performance of all air-regulated siphons? If so, will model studies become obsolete or simply complement a theoretical prediction?

69. The Authors have used an electrical analogue method to obtain equations (3a) and (3b). Could they comment on the variation of b_1 and b_2 for various inlet designs, say a reservoir siphon with a very deep inlet configuration compared with a shallow river inlet design? Would they also comment on a method of potential flow using the digital computer which will predict the shape of the streamlines, velocity and pressure at each node point and also the upstream reservoir head based on specific energy considerations? The flow area is divided by a rectangular grid into node points which are each assigned a streamflow value ψ . A finite difference relaxation technique is applied to each node based on residuals from Laplace's equation ($\nabla^2\psi = 0$) and after a number of iterations the values of ψ converge to a final solution. A typical computer plot is shown in Fig. 27 for the Eyebrook reservoir siphon at blackwater flow. Could this computer technique be applied easily at all stages of the head/discharge relationship to produce a computerized technique predicting siphon performance?

70. I am interested in the use of the energy equation $\bar{\alpha}(v^2/2g) + \bar{\gamma}z$ in determining the upstream head and hence a theoretical prediction of the head/discharge curve. From this relationship the upstream head (above lip level z) is solely a function of the inlet discharge or velocity v , and the curvature and spacing of the streamlines $\bar{\alpha}$ and $\bar{\gamma}$ at the end of the inlet lip (section 2 in Fig. 1). The implication is that for a given discharge q , the upstream head can be altered at will by changing the inlet configuration and hence the shape of the streamlines. For instance, if a very long inlet lip is used so that the curvature of the

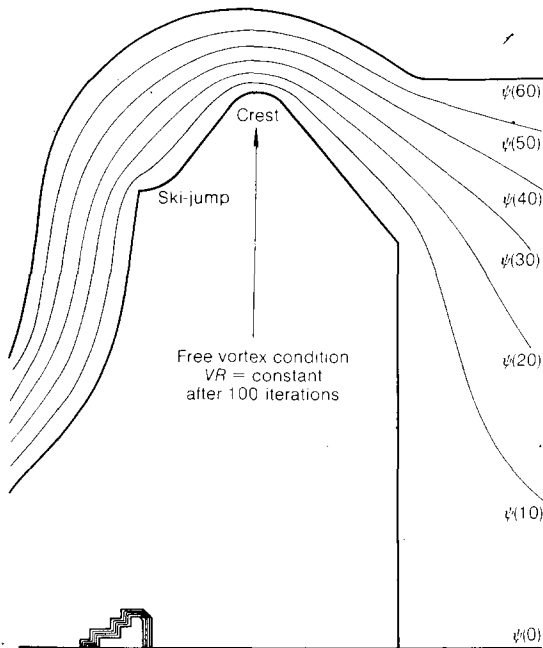


Fig. 27. High head siphon computer graph output

streamlines at the end of the inlet lip is greatly reduced and $\bar{\alpha} \rightarrow 1$ and $\bar{\gamma} \rightarrow 1$, then a flatter head/discharge curve will be produced. Do the Authors agree with this hypothesis? Would they comment on the case of a reservoir siphon where the depth of the inlet is perhaps 50 m?

71. Perhaps an oversimplification of using the energy method of predicting a siphon head/discharge curve is its lack of ability in predicting the influence of regulating air passing under the inlet lip. I have often found that vortices form at the end of the inlet lip carrying large amounts of air under the lip and the water level as a result seems to rise to throttle the influx of air.

72. It would be interesting to speculate why some siphons operate with reasonable stability with the upstream water level lower than lip level even during partialized and sub-atmospheric weir flow conditions. Can this situation be predicted from energy and irrotational flow concepts?

73. In §52 the Authors suggest a scale of 1/30 to be the minimum model size to predict prototype behaviour adequately, or at least to overcome surface tension effects to produce the classical siphon head/discharge curve. Fig. 28 compares a 1/5 scale model of the Eyebrook siphon with the full-scale behaviour of the siphon monitored over a period of 24 years.¹¹ Fig. 28(a) shows that

- (a) the lip level above crest level is small and does not produce a thick enough nappe at the point of air entrainment to ensure good air removal at the start of sub-atmospheric weir flow
- (b) the lack of air removal causes a build-up of upstream water level and

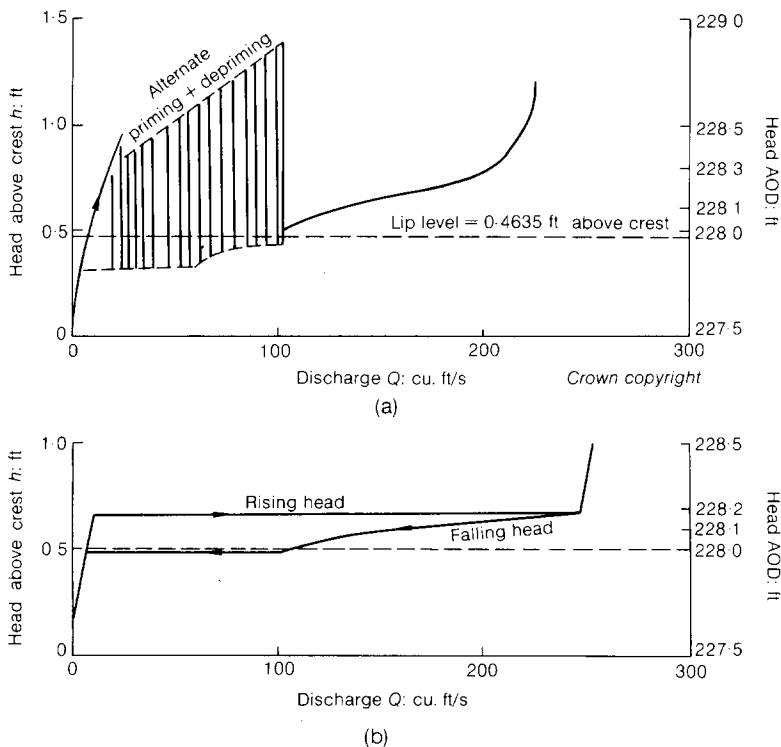


Fig. 28. (a) Results of Crump and Ackers^{1,2} for 1/5 scale model scaled up to prototype with lip level at 0.4635 ft above crest; (b) field observations of full-scale siphon with lip level at 0.5 ft above crest (1959–80)

eventually leads to hunting and surging, as indicated by the vertical lines

- (c) the hunting and surging is exaggerated in the model studies because the tank area, representing the reservoir, was too small.¹¹

74. Thus I believe that an adequate lip level, adequate air entrainment and air removal, and an upstream tank properly modelled to simulate the reservoir size accurately are all important qualifications to be added after agreeing that models as small as 1/25 or 1/30 will produce classical siphon behaviour.

Dr E. M. Elsayy, Queen's University of Belfast and Halcrow International Partnership, UAE

The aim of research on air-regulated siphons is to provide guidance for the designer before embarking on the design and modelling of such an overflow hydraulic structure. The designer's object in the first instant is to obtain siphon throat section dimensions to ensure the passage of the maximum required discharge and to design the inlet and outlet geometry to ensure air regulation and air evacuation (effective priming) respectively.

DISCUSSION

76. The Authors' experimental and analytical results of flow over the crest endorse the validity of the assumption of irrotational flow at the crest. As an overflow structure the design data available are usually the maximum water discharge and maximum upstream and downstream water levels. As a first attempt a simple free vortex approximation can be used to obtain the throat dimensions. Considering free vortex flow over the crest it can be shown that

$$Q = Br_i v_i \log_e(r_o/r_i) \quad (22)$$

where B is the siphon width, r_i and r_o are the inner and outer radii of the siphon throat, and v_i and v_o are velocities at r_i and r_o respectively. The limitation of equation (22) is discussed by Henderson.¹³

77. At blackwater flow v_i may be taken as equal to $\sqrt{(2gH)}$ where H is the driving head (the difference between upstream and downstream water levels). Equation (22) becomes

$$Q = Br_i \sqrt{(2gH)} \log_e(r_o/r_i) \quad (23)$$

Equation (23) shows that the discharge quality of a siphon is opposite to the priming quality. Reducing the crest radius r_i will increase the effective negative pressure, thus ensuring good priming, but it will reduce the discharge. The Authors concluded (§56) that as the crest radius diminishes the discharge increases, but this does not necessarily follow from equation (23). Thus it is not only cavitation which limits the reduction in the crest radius but it is also the effect on the discharge because as the crest diminishes to a sharp crested weir there is a much smaller coefficient of discharge.

78. In §44 the greatest value of C_1 was obtained with a siphon having $B/D = 2$ and from Fig. 25 the higher values of B/D also gave a lower value of C_1 . This suggests that for design purposes B/D should be bigger than 1 and less than or equal to 2. Design procedure for the siphon throat section can be as follows.

- (a) Fix r_i and r_o bearing in mind that the crest inner radius affects both the discharge and the priming quality of the siphon.
- (b) Use equation (23) to obtain the siphon width knowing the blackwater discharge and the driving head. If $B/D > 2$ choose more than one vent (siphon battery).

79. I have used the free vortex approximation to obtain the throat dimensions of the low head siphon tested by Ervine² and have computed the blackwater discharge tested by the Authors. For Head's siphon $Q = 7.14 \text{ m}^3/\text{s}$ for a driving head of 1.90 m and for Ervine's siphon $Q = 5.26 \text{ m}^3/\text{s}$ for a driving head of 2.40.

80. The Authors' analytical solution may then be used to obtain crest and air pocket pressures for various flows. The driving head may be modified accordingly as the effective head is the net result of positive and negative head at the crest. The throat dimension might have to be modified to accommodate the required maximum discharge. However, modelling will still be essential to ensure the siphon behaviour at intermediate stages between weir and blackwater flows, where the air-entrainment process is the dominant factor.

81. How did the Authors control the downstream water level? Did they increase H/D by increasing upstream water level only or by controlling the downstream level? Ervine and Elsayy^{2,8} showed that for a low head siphon the downstream water level affects the discharge significantly.

82. The tests on the sectional two-dimensional and three-dimensional models (§42) showed some difference in stage-discharge characteristics as in Fig. 24. The Authors did not show the width of the sectional model. Is this difference due to a smaller value of B/D which is in agreement with their findings on the effect of aspect ratio B/D on the coefficient of discharge?

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We expect our analytical solution (for irrotational flow) to be generally useful for all air-regulated siphons. However, it is not expected to solve certain special problems, e.g. those of vortex formation or those arising from the complicated hunting and surging phenomena. Model work will be needed for investigating such problems.

84. The parameters b_1 and b_2 are different for different siphon geometries and inlet configurations. These parameters can be obtained easily using the electric analogue method.

85. Dr Ervine's analysis is an alternative potential solution using a finite difference relaxation technique. Our analysis is much easier and gives good agreement with experiment. Also, it can be used for different siphons without the need for changing a computer program. Dr Ervine did not indicate the degree of agreement between his analysis and experimental results. We imagine that his computer program was quite elaborate. Our analysis assumes the flow to be critical over the crest of the siphon.

86. We agree with Dr Ervine's remarks regarding the effect of the length of the inlet lip on $\bar{\alpha}$ and $\bar{\gamma}$. We would expect $\bar{\alpha}$ to increase for an inlet depth of 50 m. It is easy to obtain $\bar{\alpha}$ and $\bar{\gamma}$ (without using scale models) and so it is always advisable to calculate these parameters for siphons of different geometries.

87. We also agree with Dr Ervine's remarks on air regulation under the inlet lip. Vortex formation is a complicated rotational problem which cannot be predicted from an irrotational solution. However, the air pocket pressures resulting from vortex formation are predicted accurately by our analysis. We think that our analysis can also do this for the overall siphon characteristics such as head-discharge relationships, pressures and water depths. However, it cannot explain the more complicated phenomena such as hunting and vortex formation.

88. We sympathize with Dr Ervine's reservations regarding minimum model scales. Figs 28(a) and 28(b), by displaying both model and prototype results, lead to a better understanding.

89. We agree with Dr Elsayy's design procedure but we do not think that modelling is essential to ensure the siphon's behaviour at intermediate stages between weir and blackwater flows. Our analytical solutions for head-discharge characteristics, pressures and water depths gave good results for the intermediate stages. These analytical results adequately describe the overall characteristics of the siphons studied in the Paper. Modelling is desirable for siphons with drastically different geometries. Our analytical approach should still yield useful solutions.

90. In our experiments both the upstream and downstream water depths were varied. However, when comparing the characteristics of the various sizes of siphon, care was taken to ensure that both the upstream and downstream water depths were scaled-up properly.

91. A sectional model will have $X/B = 1$. Figs 23 and 24 show the effect of this ratio on the priming curves.

References

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