2 CHARACTERISTICS OF AIR-REGULATED SIPHON SPILLWAYS

2.1 Introduction

This chapter consists of two parts. The first (Sn 2.2) gives background information about siphon spillways with definitions and a description of simple and air-regulated siphons. General criteria for siphon design are then considered. The second part (Sn 2.3) is devoted to the results of experiments on the 1:10 scale Pergau siphon model. The aim of this investigation was to gain insights into the air supply and air demand for siphon spillways. The characteristics of this model for various air inlet areas and positions are presented. The influence on the air supply of a free vortex which forms around the siphon's hood is considered in Sn 2.9.3.

2.2 A review of siphon spillways

2.2.1 Basic definitions

A ***simple siphon*** is a conduit bent into an inverted U-shape with two limbs of unequal length so that a liquid may be transferred from a higher to a lower level at a rate proportional to the difference in head. The exit from the siphon may have a water seal or it may be freely discharging to the atmosphere, but in either case the air in the conduit must be removed before the siphon runs full. During this ***priming*** process, a partial vacuum is created within the siphon as air is replaced by water.

When air is removed by the natural flow of water through the siphon it is said to be ***self-priming***. When all air is removed from the siphon barrel, priming is complete and ***blackwater*** flow commences. Alternatively, priming may be achieved with an air pump.

If a drawing down of the reservoir allows air to enter the siphon, the flow is interrupted and ***depriming*** will occur. The priming and depriming of a siphon can occur rapidly and lead to violent structural loading, but when air is allowed to enter a siphon in controlled volumes, the siphon will prime at a moderate rate and the loadings are diminished. Such an ***air-regulated siphon*** is designed for stable operation at all discharges up to blackwater flow. The difference in level between the reservoir and the siphon exit or tailwater level is known as the ***working head***. This vertical distance determines the maximum discharge available from the siphon when it carries blackwater flow. At lower discharges moderated by a flow of air through the siphon, the working head is represented by the sum of the head over the crest of the siphon, as for a conventional weir, and the subatmospheric pressure head in the barrel.

2.2.2 Development of siphon spillways

The principal of a siphon was first applied by Hirsch at Mittarsheim in 1866 but did not come into common use despite the advantages of a higher discharge per unit spillway width, the ability to pass a flood with an almost constant water level and the absence of moving parts to control operation. For many years, however, siphons were not considered for spillways owing to uncertainty about the priming process, the threat of debris blocking the throat and the danger of sudden surges downstream of the dam when the siphon primes.

The introduction of air to regulate the discharge of water through a siphon was an important innovation to ensure a smooth, gradual and controlled priming action. This led to the use of such siphons on dams and other flood control projects such as reservoirs, flood control works and hydroelectric power systems. The earliest air-regulated siphons were designed by Crump and constructed at Renala, India in 1922. In Britain one of the earliest air-regulated siphons was built at Eyebrook in 1959 (Oliver, 1959).

More recently, siphon spillways have been constructed for Spelga dam, Craigavon (Ervine, 1976), Shek Pik (Young and Tucker, 1958), Plover Cove (HRSW, 1971) and High Island (HRSW, 1973), but owing to their complex behaviour and the sparsity of design guidelines, almost all siphon spillways have had to be developed on the basis of physical model studies. A recent example is an adjustable air-regulated siphon spillway for the Pergau scheme (Hardwick and Grant, 1997). The laboratory model used for this design formed an important vehicle for the fundamental studies of the present investigation.

2.2.3 Classification of siphon spillways

2.2.3.1 Working head

One of the common ways for classifying siphon spillways is based on working head. It is often an arbitrary distinction, but it is generally accepted that a high head siphon has a working head greater than 6 m; medium head siphons operate in the range 3 m-6 m and low head siphons function under heads of less than 3 m (Ervine, 1974).

2.2.3.2 Priming method

Perhaps a more precise classification of siphons is on the basis of their priming mechanism, i.e. whether conventional or air-regulated. The conventional method involves the entrainment and evacuation of air by a nappe of water, either plunging into the sealing pool at the siphon's exit or passing over a deflector in the invert and impinging on the soffit of the siphon's barrel. Early siphon designs involving auxiliary priming devices such as baby siphons and weirs are not in common use because they are difficult to construct and are somewhat impractical.

In a conventional siphon the entry of air tending to deprime the siphon is avoided by locating the entrance well below the pond waterlevel. The downstream exit may not necessarily be sealed except during the initial priming. Thereafter, entrainment by the moving water is normally sufficient to evacuate any remaining air from the siphon. The siphon is designed to discharge water free of air, hence the name *blackwater* to describe the flow.

Air-regulated siphons, in contrast, draw in a continuous stream of air which controls the discharge through mixing with the water to form a *white-water* stream. The priming of such devices is gradual and is generally controlled by the water level of the upstream pond.

2.2.4 Principles of air-regulated siphons

A siphon spillway takes advantage of the level difference between its upstream and downstream pools; this is in contrast with a conventional spillway with atmospheric pressure at the water surface where the working head is initially the upstream water level relative to the weir crest. Once a simple siphon is primed, its full working head acting on the stream causes the discharge to increase to the maximum, blackwater flow; the drawback of such behaviour is that the siphon is essentially an on-off device where the discharge hunts between the maximum and minimum flows with levels at the intake fluctuating correspondingly. This difficulty has been overcome in certain instances through the use of multiple siphons with different crest elevations but this approach is neither elegant nor economical.

The admission of air to a siphon hood moderates the build up of flow and with the upstream water level controlling the amount of air admitted, the spillway is able to regulate the rise of reservoir level within a narrow range through a process described below. Owing to such fine control, almost the full storage capacity of the reservoir can be realised.

2.2.5 Characteristics of siphon spillways

The relationship between the reservoir level and the discharge through a siphon is the siphon's *characteristic*. Fig. 2.1 shows a typical characteristic of a simple siphon where OA represents the range of weir flow before priming is completed. Thereafter the discharge increases rapidly from A to B for virtually no increase in reservoir level. The section BC represents blackwater conditions. A lowering of reservoir level induces a rapid depriming when air enters the hood at B'. This behaviour with its hysteresis is not generally acceptable.

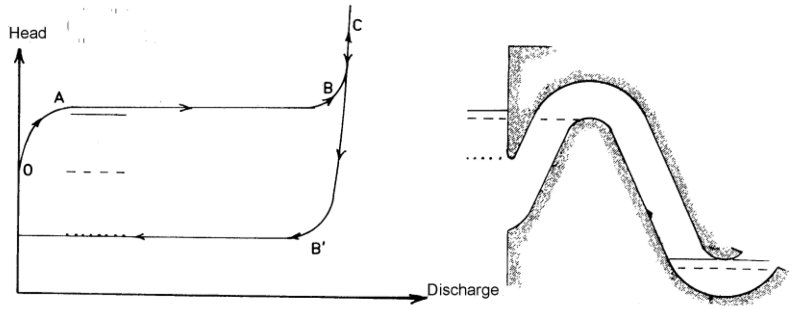


Fig 2.1 Typical characteristic of an on-off siphon spillway

An air-regulated siphon (Fig. 2.2) shows a similar weir flow section OA and then an air-regulated section A-B, where there is a gradual increase of discharge for a relatively small rise of reservoir level. When the air inlet becomes submerged, no air is admitted and blackwater conditions prevail at section BC as before. With a falling reservoir level, the flow process is reversed with no hysteresis and a virtually steady flow can be achieved for any upstream condition.

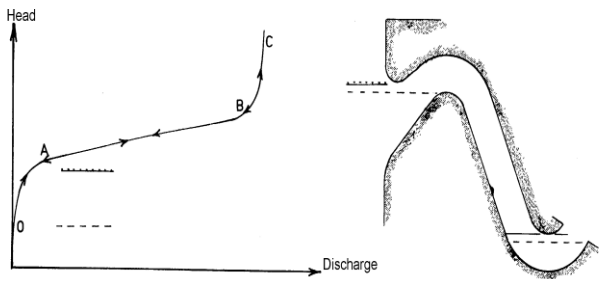


Fig 2.2 Typical characteristic of an air-regulated siphon spillway.

Fig. 2.3 shows a typical characteristic for an air-regulated siphon which incorporates the benefits of both conventional weir behaviour and closed conduit flow. Achieving an appropriate air-controlled, linking section demands an understanding of the behaviour of the air supply system and air entrainment under subatmospheric pressure. Recent researches have added to this understanding but there are still many uncertainties for designers. The present study aims to extend the knowledge of air-water mixtures with special reference to air-regulated siphons. While it may always be necessary to make physical models of novel devices, it should be possible to improve the guidance for designers at a preliminary stage, at least to define the general form of a siphon's geometry with heightened confidence.

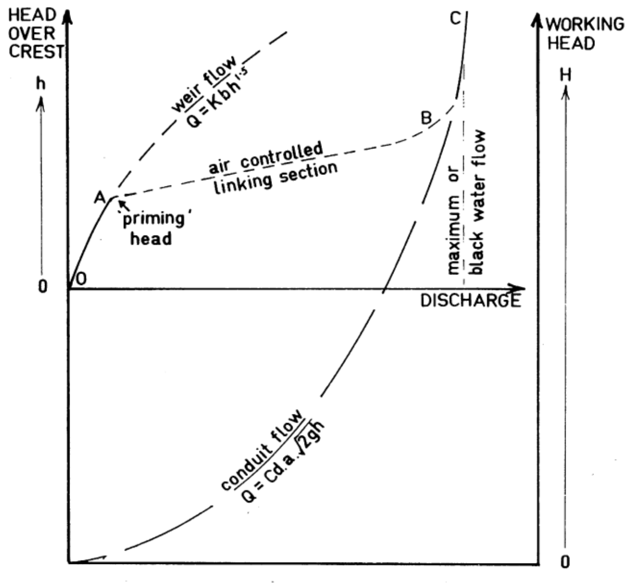


Fig 2.3 An air-regulated siphon spillway's characteristic in relation to weir and closed conduit flows (after Charlton 1971).

2.2.6 Operation of an air-regulated siphon spillway with a deflector

With a progressively rising water level in a pond, four stages of operation can be identified as described below (Charlton, 1971) and are common to the behaviour of the Pergau siphon.

2.2.6.1 Weir flow

Before priming commences the siphon operates as a conventional spillway. The descending water in the barrel approaching the deflector has insufficient momentum to be diverted to the soffit and so the pressure in the barrel remains atmospheric.

2.2.6.2 Subatmospheric weir flow

With increasing discharge, the flow in the barrel has sufficient momentum to impact on the soffit of the barrel beyond the deflector and thus seals the barrel against the ingress of air from downstream. Thereafter, air is entrained and evacuated from the spillway, the pressure falls in the barrel and there is an associated increase of water flow through the siphon which in turn evacuates more air and lowers the pressure still further. At a certain stage the pressure in the hood is so low that air is drawn through the holes in the hood and the growth of discharge is halted. Eventually a stable condition is established where the inflowing air is just equal to the outflowing air and the water discharge is held at a moderate level. There is little mixing of air and water in the descending limb of the siphon until the flow encounters the deflector.

2.2.6.3 Air-partialized flow

At still higher water discharges, culvert flow in the barrel approaches full flow with well-mixed air bubbles distributed throughout the body of the water stream.

2.2.6.4 Blackwater flow

When a further rise of reservoir level eventually seals the air holes through the hood, air-regulation ceases and blackwater flow commences. Beyond this point, an increase of discharge can be accommodated only by an appreciable rise in reservoir level. Owing to the threat of flow overtopping the dam, blackwater flow should be avoided in practice.

Head (1975), in a model study of a low-head, air-regulated siphon, identified five stages for siphon operation as: weir flow, deflected nappe, depressed/drowned nappe, air partialized flow and blackwater flow. In Head’s example the depressed/drowned condition was associated with subatmospheric weir flow conditions. Owing to the small working head, the distinction between these two phases appeared when the tailwater drowned the deflected nappe.

2.2.7 Siphon design

This section outlines some of the main considerations when developing the geometry of a siphon spillway. A well-designed structure has the following advantages over a normal overflow weir:

1. The reservoir retention level may be raised and so the storage capacity of the reservoir will be increased.
2. The stable operation of an air-regulated siphon spillway will maintain the reservoir water level within narrowly defined limits.
3. The higher working head of a siphon permits greater discharge, improved flood control and a relatively compact spillway structure.

A typical siphon characteristic (Fig. 2.3) can be used as a basis for designing a new spillway to achieve the design discharge, a certain reservoir retention level and reservoir surface level at the design discharge. Thereafter the cross-section, flow geometry, priming system and number of barrels must be established. Stages in this process are set out below.

2.2.7.1 The design discharge

The maximum discharge is determined from hydrological predictions and a routing of the design flood through the reservoir. If this flow were to be discharged in the blackwater regime, its relationship with the working head would be

$$Q_{w-\max} = C_d A\sqrt{2g\Delta H}\ , \tag{2.1}$$

where, C_d is the siphon's coefficient of discharge for blackwater flow;

A is the siphon's cross sectional area;

ΔH is the working head across the siphon between reservoir and tailwater levels.

2.2.7.2 Working head

The working head is determined from the maximum permissible flood reservoir level relative either to the centre of the siphon outlet or to the downstream water level. Its value depends on the general siphon geometry and the maximum discharge for which the siphon is to be designed. Theoretically and practically, there is no limit to the length of the siphon's downstream leg (Zanker et al, 1968), but for high-head siphons the designer must ensure that low pressures approaching the cavitation threshold in the region of the crest are avoided.

2.2.7.3 Siphon cross-sectional area

The necessary cross-sectional area of the siphon is determined from the maximum discharge, the available working head and the siphon's discharge coefficient. The resistance to flow is considered to be greatest in the blackwater regime when the siphon then functions as a closed conduit under the working head. The siphon discharge coefficient depends on the geometry of the siphon and varies between 0.65 and 0.85 (Charlton, 1971).

2.2.7.4 Priming head

Just prior to priming, the air holes in the hood are sealed but the downstream end of the siphon is vented to atmosphere, or in the case of a exit-sealed siphon, the water jet in the barrel has not achieved the threshold conditions to entrain air and evacuate the barrel from air. The pressure in the barrel remains atmospheric and the flow is thus still governed by a conventional weir relationship (OA in Fig. 2.2).

$$Q_w = Kbh_w^{3/2}, \tag{2.2}$$

where, K is the coefficient of discharge for weir flow;

b is the width of siphon's hood at the crest;

h_w is the height of water above the crest at point A in Fig. 2.3.

2.2.7.5 Exit geometry

There are two types of exit for siphons: ***exit-sealed*** and ***exit-free***. The former is the preferred type as the priming process is more certain and positive than for the latter. In cases where it is not practicable to seal the siphon's exit, a deflector is located in the barrel to divert the flow to the soffit of the conduit and so achieve a seal. Fig. 2.4 shows an exit-free installation where a battery of 16 siphons located on two sides of an eight-sided bellmouth spillway increases the reservoir retention level (Oliver, 1959).

In comparison with a sealed exit, the sealing of an exit-free design tends to be weaker; as a consequence the priming may be slower and the required head to complete the process is often higher.

2.2.7.6 Priming system

Priming systems designed in the past (Fig. 2.5) have varied from an auxiliary weir (Leliavsky, 1957) and baby siphons (Mc Birney, 1958) to the simple deflected nappe which is now considered to be most efficient for air extraction. In certain circumstances a hydraulic jump has been used successfully to prime siphons (Charlton, 1962).

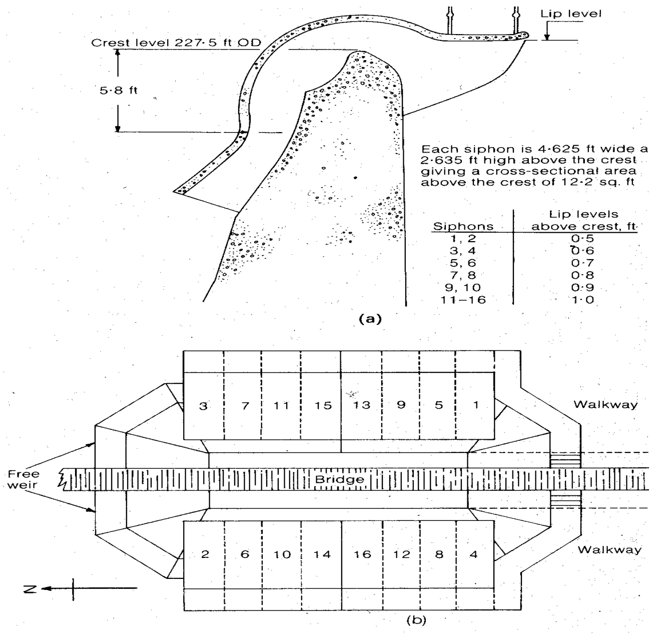
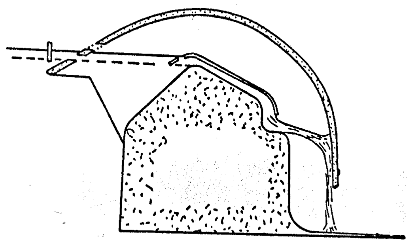
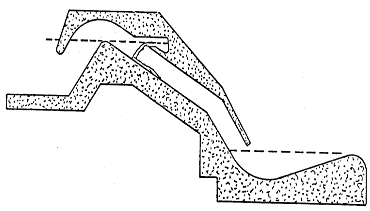


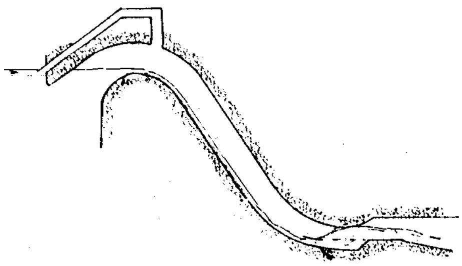
Fig 2.4 Views of Eyebrook Reservoir siphon spillway (after Ervine and Oliver, 1980).



(a) Baby siphon (after Mc Birney, 1958)



(b) Auxiliary weir (after Leliavsky, 1957)



(c) Siphon primed by a hydraulic jump (after Charlton, 1962)

Fig 2.5 Some priming systems used in siphon spillways.

2.2.7.7 Deflector

To ensure effective priming in an exit-free siphon, the deflector should continue to divert the stream as the water flow increases during the priming process; if the device is too small the increasing flow may cease to be diverted effectively and the seal will be broken. A rectangular cross-section is preferred for the barrel in the region of the deflector to ensure that the ends of the nappe retain contact with the solid boundary (Charlton, 1971). Conversely, if the deflector is too big the overall siphon resistance will be unnecessarily increased. On the strength of experiments in the present research, recommendations for the appropriate position of the deflector are given in Chapter 5.

2.2.7.8 Upper bend design

The upper bend must sustain a mixed flow of air and water around the crest of the siphon under a radial pressure gradient. It is reasonable to assume that the flow in the hood approximates to a free vortex and on this basis the radial pressure gradient for various bend radii and flow conditions may be determined. To assist the mixing of air and water, the centripetal pressure gradient should virtually neutralise the hydrostatic pressure gradient. It has been shown that a change of sign of the combined pressure gradients during the air-regulated phase can upset the air-water flow pattern and cause instability (Charlton, 1971). It is suggested, therefore, that the bend radii be selected so that over the flow range, the radial pressure gradient approaches the neutral condition but that its sign does not change. For a free vortex flow

$$u_1 = \frac{c}{R_1} \qquad \text{and} \qquad u_2 = \frac{c}{R_2}, \tag{2.3}$$

where u is the velocity, R is the radius, c is a constant and 1 and 2 refer to parameters at crest and crown respectively. If the gradient of pressure, p, in the bend is to be nearly neutral, then

$$p_1 \approx p_2 . \tag{2.4}$$

Equating the energies between crest and crown gives

$$\frac{p_1}{\rho g}+\frac{u_1^2}{2g}=\frac{p_2}{\rho g}+\frac{u_2^2}{2g}-(R_1-R_2)\,. \qquad (2.5)$$

Substituting of (2.3) and (2.4) in equation (2.5) gives an expression

$$c=R_1R_2\sqrt{\frac{2g}{R_1+R_2}}\,. \qquad (2.6)$$

Eliminating *c* from (2.3) yields

$$R_1=u_2\sqrt{\frac{R_1+R_2}{2g}} \quad \text{and} \quad R_2=u_1\sqrt{\frac{R_1+R_2}{2g}}\,. \qquad (2.7).$$

To a first approximation the velocity gradient between crest and crown may be taken as linear and then $U_{mean}=\frac{u_1+u_2}{2}$. In this way the curvature of crest and crown, appropriate to blackwater flow can be established.

2.2.7.9 Entrance and air inlet

To have stable operation and a smooth characteristic for the siphon spillway, a sufficient area of air inlet must be provided to permit the maximum demand for air to enter without restriction.

2.3 Experiments with the 1:10 scale Pergau siphon model

This section describes a series of laboratory investigations carried out with a 1:10 scale siphon model to discover the influence on air and water flows of differing areas and locations of air holes through the hood. The aims of this series of experiments were threefold:

1. to gain an increased understanding of the physical processes of siphon operation;
2. to investigate the influence on siphon behaviour of the upstream water level and
3. to investigate parameters influencing air supply and air demand in the model.

2.3.1 Apparatus

The main features of the 1:10 scale model were reported previously by Hardwick, (1992) and will be summarised here. The model (Fig. 2.6) consisted of a timber header tank 1.23 m high and 1.0 m by 1.5 m in cross section, a perspex approach channel, a perspex siphon spillway of cross-section 292 mm wide by 145 mm high with a stilling basin at the downstream end. The air inlet consisted of a line of 22 cylindrical air holes, 6.35 mm in diameter and 65 mm long located on a horizontal axis in a plane 19 mm above the siphon's crest.

The number of air holes and their elevation relative to the siphon's crest were determined through a series of trials to provide a satisfactory head-discharge characteristic for the model (Hardwick, 1992). A skimming weir drew water from the header tank to minimise undesirable level fluctuations in the approach channel arising from turbulent processes in the siphon.

2.3.2 Normal operation of the siphon

Plate 2.1 shows the main features of the flow pattern with the model operating in the air-regulated phase. The flow in the approach channel was decelerated at the protective beam adjacent to the air holes. The beam provided a quiescent pool of water between its downstream face and the air holes and it is the level of this pool which, in rising with a rising pond level, restricts the ingress of air into the hood and thus permits an increase of water discharge through the siphon.

Within the hood and above the level of the air holes, a turbulent mixture of air and water can be seen. Further downstream, this air-water mixture broke away from the soffit of the hood and air and water separated, the water forming a supercritical wall jet with a subatmospheric pressure at its surface. Near the deflector, the jet was directed toward the soffit of the barrel. The air released at the top of the barrel was drawn downstream by friction with the water jet and was entrained by the water along the length of the deflected nappe. It will be shown (Chapter 6) that the curvature of the deflected streamline increased the jet's turbulence level and so enhanced the air/water mixing.

An aerated roller may form between the nappe and the soffit of the barrel depending on the value of subatmospheric pressure in the barrel, deflection angle and the influence of higher tailwater levels with increasing discharge. In a siphon spillway on the other hand, as the air-water mixture impacts on the soffit, some of the entrained air is detrained and drawn back upstream under the impress of the barrel's subatmospheric condition. The remainder of the originally entrained air lying below a stagnating streamline is carried downstream beyond the trailing edge of the barrel where it is diffused and eventually expelled across the free surface of the turbulent stilling pool (plate 2.1).

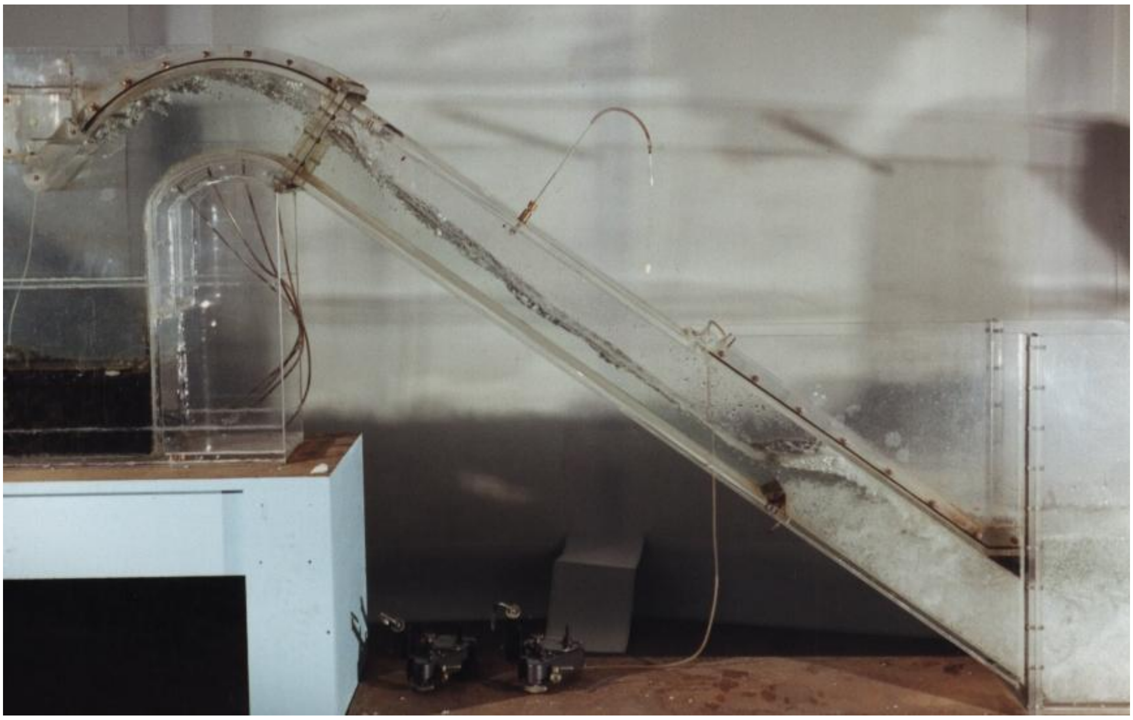


Plate 2.1 The 1:10 scale Pergau siphon model operating in the air-regulated phase.

2.3.3 Measurements of air and water flows

The water discharge through the siphon model was calculated from the pressure difference across an orifice plate located in the supply pipe to the header tank. This difference was measured using a differential mercury manometer with the accuracy of 0.5 mm. Any flow over the skimming weir was measured in a similar fashion and subtracted from the inlet flow. The airflow entering the hood through bellmouthed intakes of known cross-sectional area was deduced from the fall in pressure across these orifices. An alcohol manometer with a 1:16 amplification was used to measure this difference. Detailed descriptions of airflow measurements are given in Chapter 4.

2.3.4 Operating ranges

Typical characteristic curves relating pond elevation to water discharge are shown in Fig. 2.7 for two different air hole areas. The curves demonstrate four distinct ranges of operation: weir flow, air-regulated flow, air partialised flow and blackwater flow; these are considered in turn below.

2.3.4.1 Weir flow

The flows from 0 to about 4 l/s generated by pond elevations, y_p, up to 20 mm above the crest level had insufficient momentum to seal the barrel when negotiating the deflector. The pressure in the barrel was thus atmospheric and so the siphon operated as a conventional overflow spillway.

For slightly higher pond elevations and discharges between 4 l/s and 15 l/s, the siphon hunted between weir flow and a partially-primed condition when a temporary seal of the deflector was effected; this sealing led to a fall of pressure in the barrel and a consequent increase of discharge. This increased flow in turn caused a drawdown of the upstream pond and an exposure of the air holes such that atmospheric conditions were restored in the barrel and weir flow recommenced. Such hunting would be unlikely at full-scale because the large prototype reservoir could not be so readily drawn down. Accurate measurements of pond elevations, air flow and pressure in the barrel in this unstable range were not possible and what is plotted in Fig. 2.7 is the best estimate of average values.

2.3.4.2 Air-regulated and air-partialised flow

For pond elevations yielding discharges above 15 l/s, stable, air-regulated behaviour was initiated when a seal was effected over the deflector. As a consequence, air was evacuated from the barrel causing both a reduction of pressure and an increase of water discharge until the pressure in the hood was sufficiently low to draw in air through the air holes. This penetrating air halted both the fall of pressure in the barrel and any further increase of water discharge. A stable operating point was thus established by an equality between the air supply and the air demand. Such a flow pattern with a distinct interface between air and water in the barrel persisted for discharges up to about 60 l/s.

In the discharge range 60 l/s to 80 l/s, **air-partialized** flow was observed when the flow throughout the siphon became an air-water mixture.

2.3.4.3 Blackwater flow

The pond levels generating flows over 80 l/s submerged the air holes and blackwater flow commenced. In Fig. 2.7a, the characteristic curves show an abrupt increase of slope at this point which could lead to a rapid loss of freeboard below the top of a reservoir embankment and thus render operation in this range unsuitable at full-scale.

2.3.5 Influence of air hole area

The air hole area is seen in Fig. 2.7a to influence the slope of the characteristic curve in the air-regulated range. A reduction of air hole area led to a slight flattening of this slope which, ultimately with the provision of no air holes, becomes horizontal and the operating modes of the siphon are limited to either weir flow or blackwater flow.

2.3.6 Air flow characteristics

Airflow, Q_a, and corresponding values of subatmospheric pressure, H_{sub}, in the barrel for two air hole areas are shown in Figs 2.7b,c. It can be seen that a reduction in hole area at the beginning of the air-regulated phase tended to throttle Q_a but when the siphon progresed to air-partialized flow, the influence of hole area weakened. Three ranges of flow are identified in Fig. 2.7b. Maximum Q_a is observed at the commencement of the first range (**i**) and thereafter, as Q_w increased, Q_a decreased sharply as the water level in the hood progressively rose toward the crown of the siphon in a process which appeared to impede the inflow of air.

In the second range (**ii**), Q_a was virtually constant and it will be seen later that this is probably the result of two opposing processes: the rising pond level on the one hand tending to restrict the air supply while on the other, the corresponding increase of Q_w tending to increase air entrainment near the deflector. In the third range (**iii**), Q_a increased, owing to the formation of what was understood to be a free vortex in the hood of the siphon (Sn 2.3.9). Greater measured levels of subatmospheric pressure at the crown than those further downstream in the barrel are consistent with this idea and the generally lowered pressure in the hood led to increased Q_a through the air holes. Beyond range (**iii**), the air supply was increasingly throttled until blackwater flow prevailed, the scattered results indicating the difficulty in measuring both Q_a and H_{sub} in unsteady flow conditions.

Over the discharges associated with ranges (**i**) and (**ii**), Fig. 2.7c shows a steady increase of subatmospheric pressure with increasing Q_w which reflects the growing entrainment of air by a more vigorous mixing process in the region of the deflector. In range (**iii**), this growth of H_{sub} appeared to be moderated by the greater supply of air noted above in connection with free vortex action. The slight trend toward higher values of H_{sub} with reducing hole area will be seen later to be more marked when the air hole area is further diminished. Beyond range (**iii**), where blackwater conditions develop and pressure measurements were less reliable, the trend of H_{sub} toward lower values is nevertheless clear.

The parameters shown in Figs 2.7a,b,c are linked by the siphon's geometry and flow pattern; in an attempt to eliminate the influence of pond level on Q_a, the 1:10 scale model was modified in the following way (Sn 2.3.7):

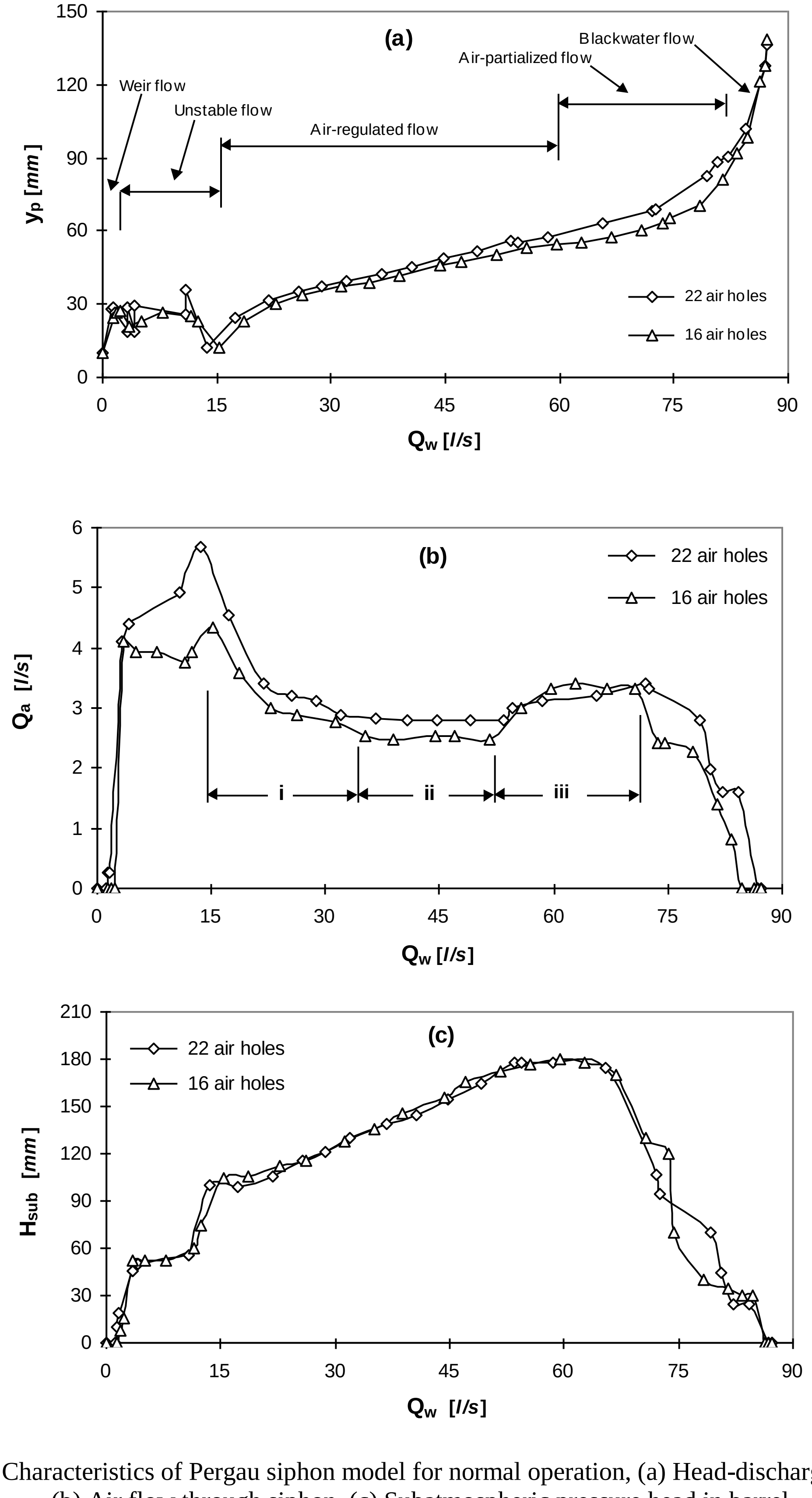


Fig 2.7 Characteristics of Pergau siphon model for normal operation, (a) Head-discharge curves, (b) Air flow through siphon, (c) Subatmospheric pressure head in barrel.

2.3.7 An attempt to deduce air demand

As a means of breaking the link between air supply and air demand, the entrance to the inner pool between the beam and the air holes was sealed such that conditions upstream had no influence on the air hole inlets. Measurements of head, discharge, airflow and pressure were repeated and the results presented in Fig. 2.8.

An unobstructed supply of air prevented blackwater flow (c.f. Figs 2.8a and 2.7a) and reduced the gradient of H_{sub} (c.f. Figs 2.8c and 2.7c). Higher pond elevations relative to the weir crest, y_{p}, were generally necessary to yield a given discharge because of these reduced levels of H_{sub}. In range (**i**) of Fig. 2.8b, the rising level of water in the hood with increasing Q_w again progressively reduced Q_a. It will be shown in Chapter 3 that a rising waterlevel above the air hole elevation reduced the driving head for Q_a and as a result the rate of air entering the siphon decreased.

In range (**ii**) with no further change of flow geometry in the hood and no restriction on the entry of air, Q_a increased in response to the formation the free vortex flow in the hood. Another important agent for increasing airflow was the change in the flow pattern over the deflector with increasing Q_w. The thicker water jet with higher momentum was deflected at a lower angle to the horizontal, impinging on the siphon's soffit with a milder angle so that the roller above the nappe diminished in size and almost all the entrained air was transported by the water out of the siphon. This entrainment was offset to some extent by both the influence of an increasing H_{sub} tending to increase the size of the roller and a rising pressure downstream of the deflector imposed by a higher tailwater. Toward the end of range (**ii**), Q_a tended to become constant and the gradient of H_{sub} diminished with the onset of air partialisation when the entraining processes near the deflector were suppressed; to maintain an increase in $Q_{w,}$ the response of the siphon to such a reduced gradient for H_{sub} was seen in a steeper gradient for y_p in Fig. 2.8a.

As before, a reduction of air hole area generally reduced both y_p and Q_a and increased H_{sub}, but this attempt to break the link between air supply and air demand failed owing to the effects of a varying flow pattern in the hood; the rise of water level towards the crown in range **(i)** and the suggested free vortex effect at higher flows tended respectively to reduce and increase the gradient of $Q_{a.}$ In an effort to eliminate these influences, an alternative air inlet was devised as described below.

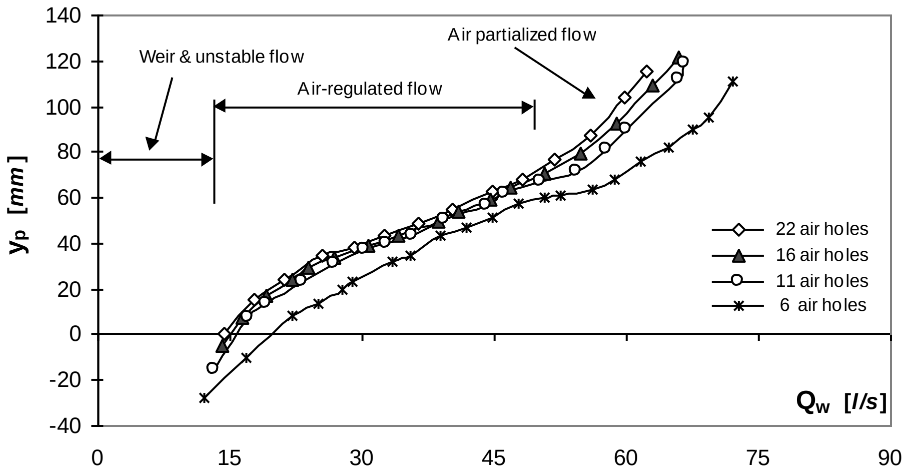
2.3.8 Air inlet downstream of the hood

To deduce the air demand arising solely from the entrainment / detrainment process near the deflector, the air holes through the hood were sealed and new holes were opened in the soffit of the barrel, well downstream of the siphon's crest where they would be unaffected by changes of flow pattern in the hood. It was also considered that such an arrangement would show the influence of H_{sub} in detraining air from the mixing zone near the deflector. The results of tests for this new air inlet location with a combination of hole areas identical to those used previously are shown in Fig. 2.9

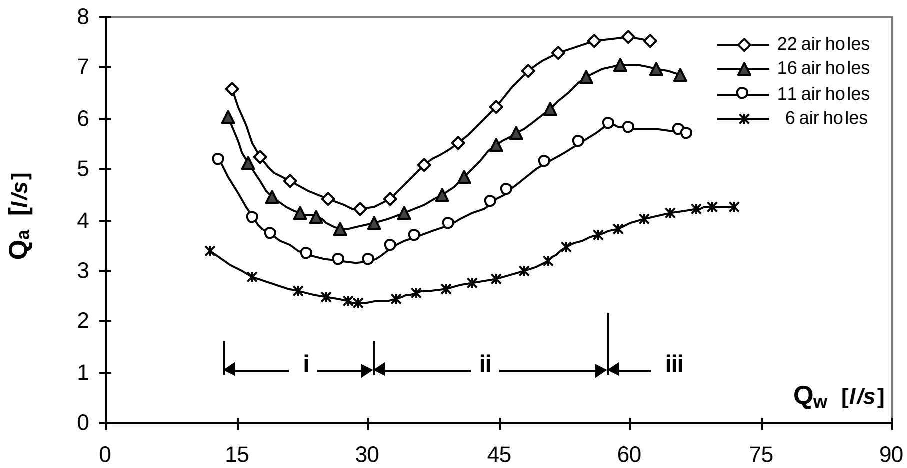
The head-discharge curves of Fig. 2.9a are in marked contrast with those previously considered and show regions where stable operating conditions could not be achieved. For discharges up to about 4 l/s, weir flow was seen over the crest of the siphon until a seal developed over the deflector and siphonic flow commenced. This transition was most obvious for the smallest hole area where the pond elevation was rapidly drawn down and there was a step-increment in discharge. At this transition, H_{sub} increased sharply from near-atmospheric conditions but the unobstructed access of air limited its rise to levels which were generally below those shown in Figs 2.7 and 2.8; increases of water discharge were thus mainly achieved by an increase of pond elevation.

At a discharge of about 30 l/s in Fig. 2.9a, the flow pattern again changed with a migration of the water surface towards the crown of the siphon and the development of free vortex action in the hood. At this point there was a step-fall in pond elevation and a step-rise in H_{sub}.

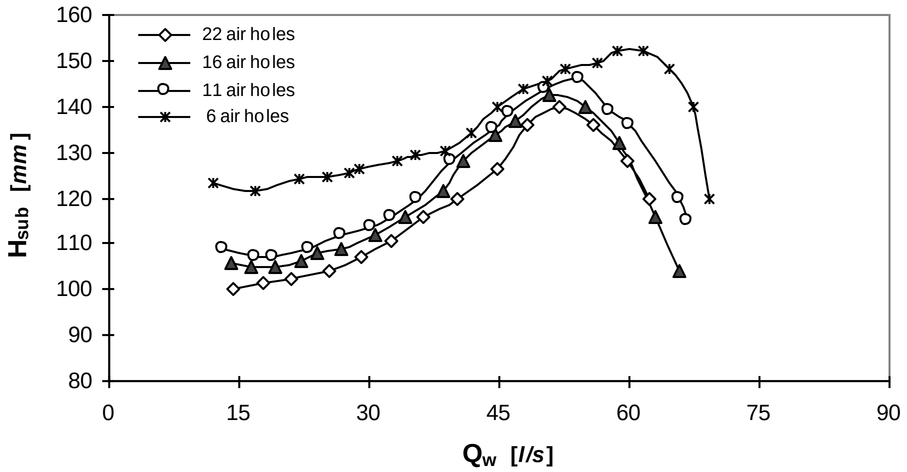
The trends for Q_a in Fig. 2.9b show a common increase of air demand until point **A** in the figure when, for the smallest air hole area, an equilibrium was achieved between a tendency to greater air entrainment with increasing Q_w and a tendency to greater detrainment owing to higher values of H_{sub}. With larger air hole areas, this equilibrium was established at points **B** and **C** at higher values of Q_w.



(a) Head-discharge curves

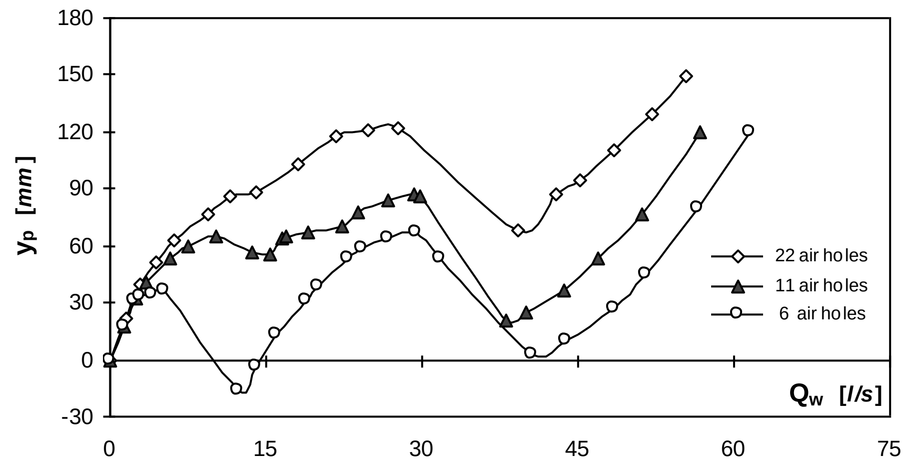


(b) Air demand curves

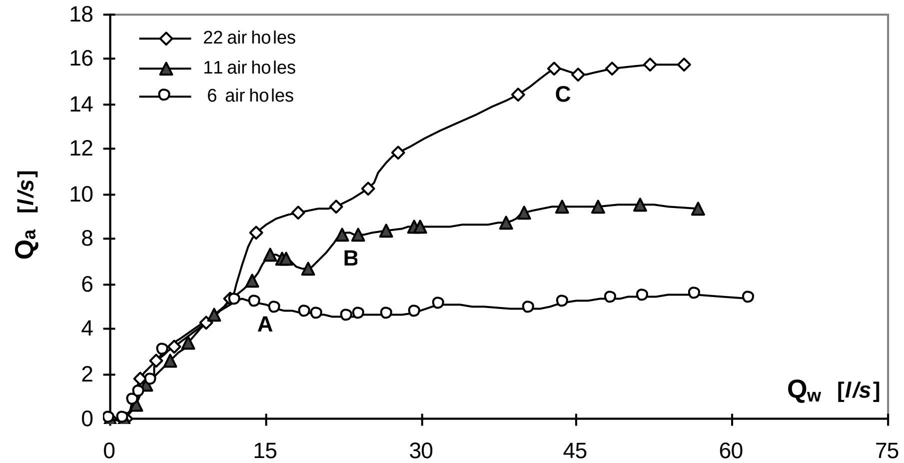


(c) Subatmospheric pressure head in barrel

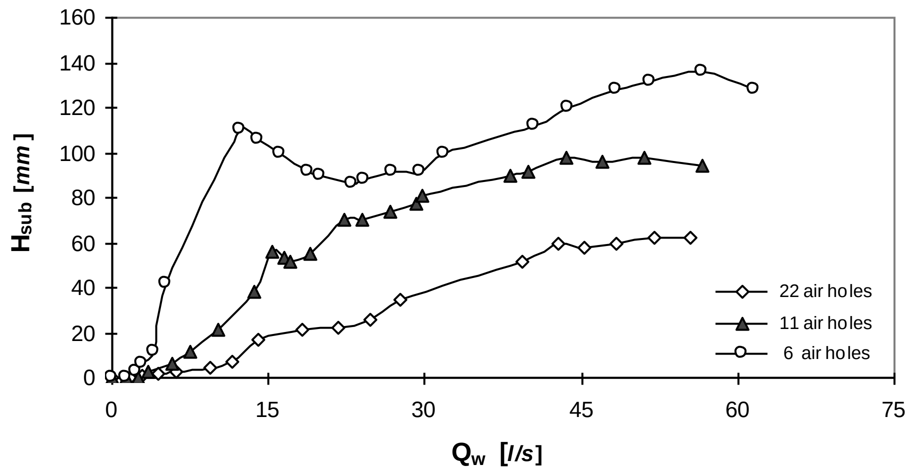
Fig 2.8 Characteristics with inlets to air holes unrestricted.



(a) Head-discharge curves



(b) Air demand curves



(c) Subatmospheric pressure head in barrel

Fig 2.9 Characteristics for an air inlet downstream of the siphon's crest.

2.3.9 Influence of a free vortex in the siphon's hood

The rate of airflow in siphon spillways generally depends on the characteristics of the siphon's air supply and the air demand of the water jet over the deflector.

It was recognised from the experiments performed on the Pergau model described in this chapter that the major parameters influencing *air supply* were as follows (Fig. 2.10): the waterlevel upstream of the air hole, y_a, the cross-sectional area of the air holes, A_a; the height of water above the air holes in the hood, Z; and the subatmospheric pressure in the siphon's hood. The air *demand* was found to be influenced by the flow pattern and water jet velocity at the deflector, the surface roller and the angle of the jet impingement on the siphon's soffit and the downstream water level. The subatmospheric pressure in the hood acted as the driving head for airflow entering the siphon and also served as an agent for controlling the angle of jet impingement and the associated roller above the nappe which detrained part of the originally entrained air back to the barrel.

It is believed that the formation of a free vortex in the siphon's hood affected both the supply of air to the siphon and the demand for air over the deflector. To examine this idea, precise measurements of all the above parameters were performed when the siphon was operating in the normal condition with air entering 22 holes through the hood (Fig. 2.6). Fig. 2.11 shows the variation with water flow, Q_w, of the following: the airflow, Q_a; the subatmospheric pressures in the hood at the level of air holes, $H_{sub\text{-}hole}$ (Fig. 2.10); the subatmospheric pressure at the siphon's crown, $H_{sub\text{-}crown}$, and above the water jet in the barrel, $H_{sub\text{-}barrel}$. The variation of waterlevel upstream of the air holes is plotted in Fig. 2.12.

In this section, attention is mainly concentrated on the variation of subatmospheric pressure in the hood. Fig. 2.11, shows for $Q_w \leq 30$ l/s that $H_{sub\text{-}hole}$, the driving head for air entering the siphon, experienced a slight fall; the corresponding fall of Q_a is believed to be partly due to the obstruction of air holes by the upstream water level, y_a, (Fig. 2.12) but more importantly, the decreasing subatmospheric pressure in the hood as the water level above the air holes, Z, rose. In the range $30 \prec Q_w \leq 50$ l/s, Q_a remained virtually constant where Z reached its upper limit at the siphon's crown. In this range there appeared to be a balance where the increasing $H_{sub-barrel}$ (tending to increase Q_a) is opposed by the gradual obstruction of the air holes together with the increased detrainment by the roller.

For $Q_w \succ 50$ l/s, it was suggested that a free vortex flow formed in the hood around the siphon's crest. Fig. 2.11 shows an increase in the subatmospheric pressures in the hood, $H_{sub-hole}$ and $H_{sub-crown}$, and despite the increase of y_a, Q_a increased. The additional air supplied to the siphon in this range diminished the gradient of the subatmospheric pressure in the barrel; this led in turn to a milder angle of impingement of the deflected nappe on the siphon's soffit and less detrainment of air from the roller.

In an attempt to confirm the formation of free vortex flow in the hood for $Q_w \succ 50$ l/s, it was decided to compare the measured water discharge with that predicted by an equation developed for an ideal fluid in a rectangular conduit bend (Webber, 1993) as:

$$\frac{p_2 - p_1}{\gamma} = \frac{Q_w^{\ 2}}{2g[bR_1 Ln(R_2 / R_1)]^2}[1-(R_1 / R_2)^2], \qquad (2.8)$$

in which 1 and 2 refer to the parameters at the inner and outer radii of the bend in the horizontal plane respectively. For a siphon's hood in the *vertical* plane, the difference in pressure head at the crown and crest would be

$$H_2 - H_1 = \frac{Q_w^{\ 2}}{2g[bR_1 Ln(R_2 / R_1)]^2}[1-(R_1 / R_2)^2] - (R_2 - R_1), \qquad (2.9)$$

where, b is the throat width and H_2, R_2 and H_1, R_1 are pressure head and radius at the crown and crest respectively.

The ratio of predicted discharge, Q_{w-p}, (Eqn 2.9) to the measured discharge, Q_{w-m}, together with the variation of subatmospheric pressure in the hood and barrel, are shown in Fig. 2.13. It is seen that for $Q_w \succ 50$ l/s, the ratio of Q_{w-p}/Q_{w-m} reached a fairly constant value of about 1.3 and appeared to confirm the development of free vortex flow in the hood. The 30% difference between the measured and predicted discharges is believed to be due to general turbulence in the mainstream and boundary layer friction.

Fig. 2.11 shows that for $Q_w \succ 70$ l/s, despite the increasing H_{sub} in the hood, the airflow decreased to zero as the air holes were deeply submerged by the upstream water level, y_a, (Fig. 2.12). The fall of H_{sub} values evident in Fig. 2.11 reflects the complete filling of the barrel as blackwater conditions developed.

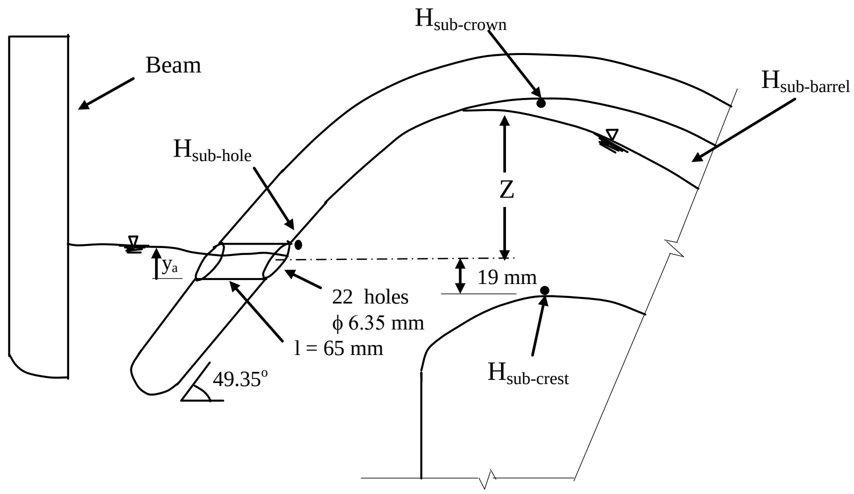


Fig 2.10 Parameters influencing free vortex flow in the siphon's hood (Not to scale).

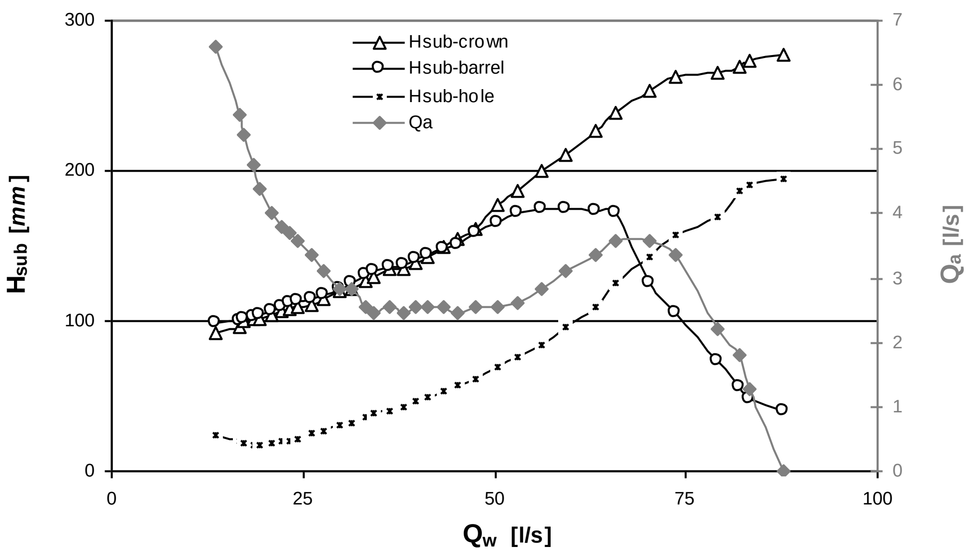


Fig 2.11 Variation of Q_a and H_{sub} in the siphon's hood and barrel.

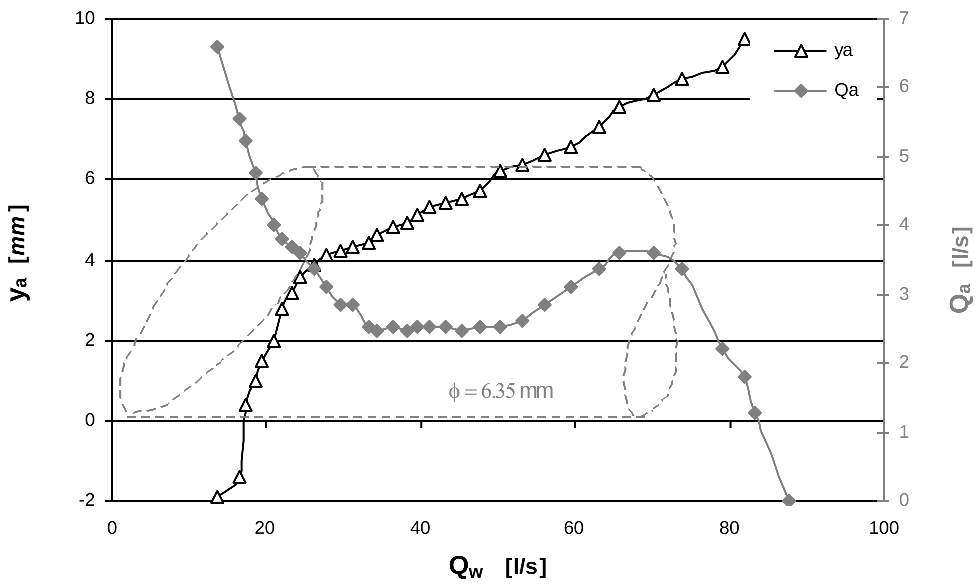


Fig 2.12 Variation with Q_w of Q_a and the upstream water level relative to the invert of the air holes.

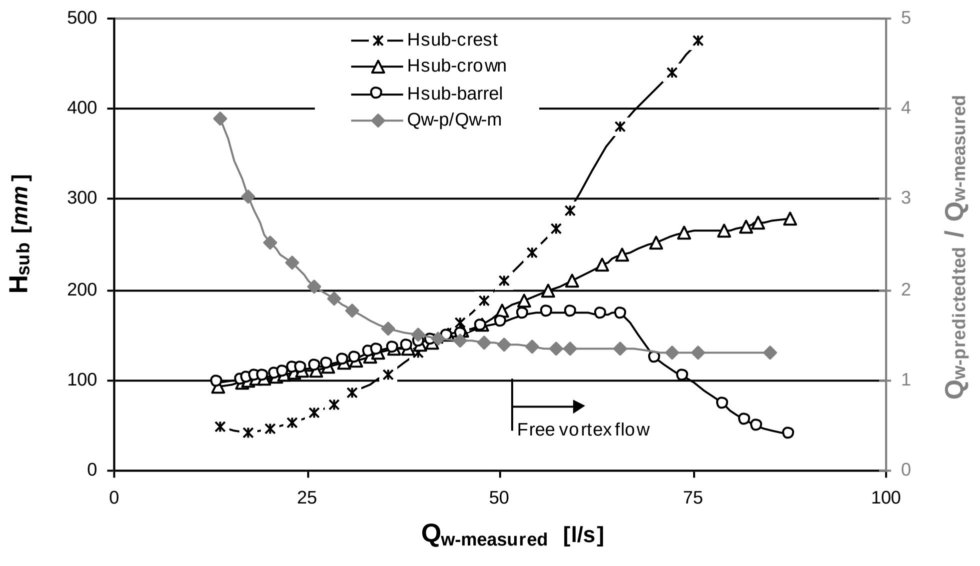


Fig 2.13 The ratio of predicted water discharge for free vortex flow in the hood and the measured discharge in the siphon model.

2.4 Summary

The results of experiments on the Pergau siphon model can be summarised as follows:

1. For the siphon geometry of Fig. 2.6, the water discharge, $Q_{w,}$ was found to depend on

   i a combination of pond elevation, y_p, and subatmospheric pressure, H_{sub};

   ii air hole area which was further modified by the rising waterlevel upstream of the air holes, y_a, as Q_w increased and

   iii varying flow patterns in the hood and near the deflector which altered the supply and demand curves for air.

2. The air entering the siphon depended on the air supply and demand characteristics. It was found that the height of water in the hood above the level of the air holes, the subatmospheric pressure in the hood and the formation of a free vortex flow around the siphon's crest all had an influence on the air supply.

3. In addition to the turbulence level in the deflected stream, the angle between the impinging nappe and the siphon's soffit was found to influence the air demand, the maximum occurring when a mild angle generated no roller above the nappe.

4. For the geometry represented in Fig. 2.8 where the hole area remained constant, the air demand characteristics were no longer influenced by (ii) above and blackwater conditions were eliminated, but the influence of (iii) above remained.

5. The geometry relating to Fig. 2.9 with air holes beyond the crown provided the desired air demand curve because it was believed to be uninfluenced by the air supply characteristics.

In an attempt to gain a deeper understanding of the air supply process itself, a simplified siphon model was developed as described in the following chapter.