Influence of cross-section geometry on air demand ratio in high-head conduits with radial gate

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ABSTRACT

When the gate of a high-head conduit is partly opened, a negative pressure draws the air in through the air vent. Air that is entrained into the water is instantly forced downstream in the form of air bubbles. When the studies on high-head gated conduits were examined, it was determined that the air demand ratio varied depending on many hydraulic and geometric parameters. This work focused on determining the effect of conduit cross-section geometry on the air-demand ratio. A series of experiments were carried out on high-head radial gated conduits having different cross-section geometries. Experimental results showed that conduit cross-section geometry was an important effect on the air demand ratio especially in small gate opening rates. Further, design equations for the air demand ratio were presented relating the air demand ratio to Froude number, gate opening rate, and ratio of gate opening to conduit length.

Key words: air demand, conduit, cross-section geometry, high-head flow, radial gate

HIGHLIGHTS

• An experimental study was conducted to investigate Qa/Qw of gated conduits.
• Qa/Qw of the gated conduit was investigated by using different cross-section geometry.
• High head conduits can be used efficiently in the aeration of water.
• The cross sectional geometry does not have a significant effect on Qa/Qw at the gate opening rates greater than 10% gate opening rate.
• Equations was developed to estimate Qa/Qw.

NOTATIONS

| Symbol | Description |
|--------|-------------|
| Aw     | water flow cross-section area |
| B      | water surface width |
| Fr     | Froude number |
| g      | acceleration of gravity |
| h      | gate opening |
| h1     | gate height |
| he     | effective depth |
| L      | conduit length |
| Qa     | air flow rate measured through air vent |
| Qa/Qw  | air demand ratio (\( \beta \)) |
| Qw     | water flow rate in conduit |
| R      | hydraulic radius |
| V      | water flow velocity at gate location |
| \( \varphi \) | ratio of water flow cross-section area to conduit cross-section area |

INTRODUCTION

High-head gated conduit is widely used for various purposes such as emergency draining of dam reservoir, regulation of water level in reservoir, preventing sediment accumulation at dam base, aeration in water and wastewater treatment, etc. The velocity of the flow passing under the gate in the conduit increases due to the narrowing in the section. High-speed flow can cause various structural damage, such as cavitation, due to the effect
of the micro-bubbles it contains (Tullis 1989). Cavitation begins to occur as soon as the pressure in the conduit drops to the vapor pressure value. Cavitation bubbles with increasing dimensions and moving with the flow explode together with the increase of the pressure and lead to structural damage. To reduce or eliminate this damage, air vents are placed downstream of the gate where the flow speed is high. By using the air vent, the air in the atmosphere is drawn into the conduit and the pressure of the gate downstream is kept at safer levels (Figure 1).

The air demand ratio and the aeration efficiency in closed conduits have been studied experimentally many researches (Kalinske & Robertson 1943; Campbell & Guyton 1953; USACE 1964; Wisner 1965; Sharma 1976; Speerli and Hager 2000; Ozkan et al. 2006, 2014, 2015; Oveson 2008; Unsal et al. 2008, 2009; Tuna et al. 2014).

The first study on air demand ratio in conduits was carried out by Kalinske & Robertson (1943), who associates hydraulic jump with air inlet in circular conduits and determine that the air inlet is a function of the Froude number downstream of the hydraulic jump. In their physical models, they expressed the air demand ratio by the Froude number and developed the following equation.

\[
\beta = \frac{Q_a}{Q_w} = 0.0066 \left( \frac{Fr}{C_0} \right)^{1.4}
\]

(1)

where \( \beta \): air demand ratio (\( Q_a/Q_w \)); \( Q_a \): flow rate of the air measured from the air vent (m\(^3\)/s); \( Q_w \): water flow rate through the conduit (m\(^3\)/s); \( Fr \): Froude number.

The results of Kalinske & Robertson (1943) have been analyzed and modified by several researchers to provide a basis for estimating the air demand ratio in such applications (Campbell & Guyton 1953; Haindl ve Sotornik 1957; Rajaratnam 1962; USACE 1964; Levin 1965; Wisner 1965; Sharma 1976; Falvey 1980; Speerli and Hager 2000; Shamsaei 2006). These results are given in Table 1.

According to the results obtained from these studies, it is stated that the only parameter affecting the air demand ratio is the Froude number. However, in many subsequent studies, it has been determined that many hydraulic and geometric parameters affect the air demand ratio (Dettrmers 1953; Gongchun & Chupei 1987; Unsal et al. 2008, 2009; Tuna et al. 2014).

![Figure 1](http://iwaponline.com/ws/article-pdf/doi/10.2166/ws.2021.162/894795/ws2021162.pdf)

**Figure 1** | Two-phase flow in gated conduits.

| Table 1 | Predictive equations for air demand ratio in conduits |
|---------|-------------------------------------------------------|
| **Campbell & Guyton (1953)** | \( \beta = 0.04(\frac{Fr}{1})^{0.85} \) |
| **Haindl & Sotornik (1957)** | \( \beta = 0.012(\frac{Fr}{1})^{1.4} \) |
| **Rajaratnam (1962)** | \( \beta = 0.018(\frac{Fr}{1})^{1.245} \) |
| **USACE (1964)** | \( \beta = 0.03(\frac{Fr}{1})^{1.06} \) |
| **Wisner (1965)** | \( \beta = 0.024(\frac{Fr}{1})^{1.4} \) |
| **Sharma (1976)** | \( \beta = 0.09(\frac{Fr}{1})^{0.96} \) for free surface flow  
\( \beta = 0.2(\frac{Fr}{1}) \) for spray flow |
| **Shamsaei et al. (2006)** | \( \beta = 0.0555(\frac{Fr}{1})^{0.7869} \) |
Hager & Bremen 1989; Hager et al. 1990; Speerli & Volkart 1997; Ervine 1998; Aydin 2002). Dettrmers (1953) stated in their research at the Lumiei Dam that the air inlet is associated with the geometry of the gate structure, independent of pressure, and the air demand ratio is mainly influenced by the geometry of the gate structure (Sharma 1976). In addition, no detailed study investigating the effect of cross-section geometry on air demand ratio has been reached. Based on this information, the effect of cross-section geometry on air demand ratio in high-head radial gated conduits was investigated in the scope of this study. Unlike other studies, a radial gate was used to reduce head losses.

**MATERIAL AND METHOD**

**Experimental setup**

In this study, the effects of physical parameters such as different cross-section geometries, gate opening rates, conduit lengths, and water flow rates on the air demand ratio were investigated. A physical experimental setup was built at Firat University Hydraulic Laboratory. All components used in the experimental setup are shown in Figure 2. The water, which has a certain volume in the experiments, has been circulated continuously. The water in the tank was transmitted to the conduit by pressure. For this purpose, an 11.2 kW powered water pump was used. The flow transmitted to the system was adjusted with the help of a flow control valve. Water flow rates were measured using a calibrated electromagnetic flow meter. To eliminate head losses, the diameter of the pipeline that transmits the water to the conduits has been chosen in the same size with the pump outlet diameter (3-inch diameter).

Three different conduit cross-sections were used to investigate the effect of the cross-section geometry on air demand ratio (Figure 3). Rectangular conduits were chosen in width: 60 mm × height: 100 mm and width: 100 mm × height: 60 mm dimensions to have the same cross-section area with a circular conduit having a 3-inch diameter.

![Figure 2](http://iwaponline.com/ws/article-pdf/doi/10.2166/ws.2021.162/894795/ws2021162.pdf)

Figure 2 | (a) Laboratory high-head radial gated conduit apparatus, (b) Experimental procedure.
In this study, unlike the studies in the literature, a radial gate was used to reduce head losses (Figure 4). The radius of the radial gate was chosen by taking into account the required gate height at the minimum gate opening ratio. The gate radius is determined as 87.6 mm, which is the largest value of gate height (h₁) given in Table 2. The radial gate with the same curvature was used in all experimental series.

Gate opening rates for all cross-section geometries were chosen as 10, 15, 20, 30, 40, and 60% (Table 3). The gate opening ratio refers to the ratio of water flow cross-section area to conduit cross-section area.

1 m, 2 m, 4 m, and 6 m long conduits were used to investigate the effect of conduit length on air demand ratio (Figure 5(a)). Some preliminary experiments were carried out before the main experiments were conducted. In these preliminary experiments, it was determined that air flow rate measured through air vent was very low in conduit lengths longer than 6 m. For this reason, a maximum conduit length was determined to be 6 m.

An air vent having 200 mm high was placed downstream of the gate to entrain air into water. The air velocity entering the system was measured with the help of a Testo Model 435 anemometer. The diameter of the air vent was 15 mm, 30 mm and, 45 mm. (Figure 5(b)). Air flow rate measured through air vent (Qₐ) was very slow in low water flow rates (Q₉). Because the anemometer cannot measure small air velocities, to eliminate this sensitivity of the anemometer, 15 and 30 mm diameter air vents were used in low water flow rates.

While transmitting the water flow from the circular pipe to the rectangular conduit, the reductions were used to minimize head losses (Figure 5(c)).

![Figure 3](image1.png) Conduit cross-section geometries.

![Figure 4](image2.png) Rectangular cross-section conduits with radial gate.

| Gate opening rate (ω) | 60 × 100 h₁ (mm) | 100 × 60 h₁ (mm) | Circular h₁ (mm) |
|----------------------|------------------|------------------|-----------------|
| 10%                  | 87.6             | 51.6             | 74.9            |
| 15%                  | 82.9             | 48.9             | 70.8            |
| 20%                  | 78.2             | 46.2             | 67.1            |
| 30%                  | 68.8             | 40.8             | 60.1            |
| 40%                  | 59.4             | 35.4             | 53.5            |
| 60%                  | 40.6             | 24.6             | 40.76           |
Experimental procedure

The air velocity was measured directly in the air vent by using the anemometer and was used to determine the air flow rate. This measurement was accomplished by locating the anemometer at the center of the air vent. Each air velocity measurement was taken over for 60 sec or longer. The anemometer used for air velocity measurements was accurate to \( \pm (0.2 \text{ m/s} + 1.5\% \text{ of } \text{m}) \). Care was taken to ensure that the anemometer was always perpendicular to the direction of flow in the air vent to provide the most accurate measurements possible. After obtaining a
value of the air velocity, the air flow rate was calculated by multiplying the air velocity and the air vent cross-section area. The determined water flow rates were measured using a calibrated electromagnetic flow meter. A total of 504 experiments were carried out. The experimental series are given in Table 4.

The Froude number, which is a dimensionless number that takes into account the inertia and gravitational forces and does not take into account the viscous or surface tension forces, was determined with Equation (2).

In the literature, the Froude number has often been based on the vena contracta section. However, to avoid the problem due to the flow velocities and depths at the vena contracta in high-head gated conduits containing high-velocity air-water flow, in this study, the Froude number was associated with the effective depth in the conduit.

\[
Fr = \frac{V}{\sqrt{gh_c}} \tag{2}
\]

where \(V\): water velocity at gate location; \(g\): gravity acceleration; and \(h_c\): effective depth (ratio of water flow cross-section area to water surface width).

\[
h_c = \frac{A_w}{B} \tag{3}
\]

where \(A_w\): water flow cross-section area; \(B\): water surface width (Figure 6).

**EXPERIMENTAL RESULTS**

The purpose of this research was to determine the effect of conduit cross-section geometry on the air demand ratio. This objective was achieved by building a physical experimental setup, conducting experiments, obtaining data, analyzing the data, and presenting the results.

Figures 7–12 show plots of air demand ratio \((Q_a/Q_w)\) with Froude number \((Fr)\) for conduit cross-section geometry, gate opening rate \((\phi)\), and conduit length \((L)\). As can be seen in these figures, conduit cross-section
Figure 7 | The variation of \( Q_a/Q_w \) with the Froude number for \( \varphi = 10\% \) and \( L = 1, 2, 4, 6 \) m.

Figure 8 | The variation of \( Q_a/Q_w \) with the Froude number for \( \varphi = 15\% \) and \( L = 1, 2, 4, 6 \) m.
Figure 9 | The variation of $Q_a/Q_w$ with the Froude number for $\varphi = 20\%$ and $L = 1, 2, 4, 6$ m.

Figure 10 | The variation of $Q_a/Q_w$ with the Froude number for $\varphi = 30\%$ and $L = 1, 2, 4, 6$ m.
Figure 11 | The variation of $Q_a/Q_w$ with the Froude number for $\varphi = 40\%$ and $L = 1, 2, 4, 6$ m.

Figure 12 | The variation of $Q_a/Q_w$ with the Froude number for $\varphi = 60\%$ and $L = 1, 2, 4, 6$ m.
geometry affects the air demand ratio at the minimum gate opening rate (10%). The best air demand ratio was observed in the circular conduit having a 2 m conduit length and gate opening rate of 10%. The circular cross-section conduit was advantageous in terms of air demand ratio compared to other cross-section conduits. However, it was observed that as the gate opening rate increased, the effect of conduit cross-section geometry on air demand ratio decreased.

It was observed from Figures 7-12 that as the gate opening rate increased, although the Froude number increased, the increasing trend of $Q_a/Q_w$ ceased and $Q_a/Q_w$ remained unchanged after a certain Froude number.

In the rectangular cross-section conduits, less water flow rate was transmitted since the dead volume was greater than that in the circular cross-section conduit. When the air flow rate measured through the air vent was examined, it was determined that the circular cross-section conduit drawn more air flow rate than the rectangular cross-section conduits.

Although in the circular cross-section conduit the air flow rate ($Q_a$) measured through the air vent was more than that in the rectangular cross-section conduits, the $Q_a/Q_w$ reached the same values with the rectangular cross-section conduits. The reason for this was that the water flow rate ($Q_w$) in the circular cross-section conduit was higher than that in the rectangular cross-section conduits. Therefore, it was shown that conduit cross-section geometry did not have a significant effect on the air demand ratio.

In the maximum gate opening rate (60%), the air demand ratio had generally minimum values. The reason for this was that as the gate opening rate increased, a weak hydraulic jump occurred due to the decrease in the Froude number.

The lowest air demand ratio was generally observed at the minimum conduit length (1 m). The reason for this is thought to be the hydraulic jump. Previous researches showed that hydraulic jump had a significant effect on the air demand ratio. It was determined that the air intake started with the hydraulic jump and the length of the aerated zone continued even if the jump ended. The air demand ratio decreased as no hydraulic jump occurred in very small conduit lengths.

**DATA ANALYSIS**

Separate equations have been developed for each conduit cross-section geometries considering all the parameters mentioned in this study. Nonlinear regression was used to determine the constants of the equations. The developed equations are shown in Table 5.

The measured air demand ratio values were compared with those computed with the equation developed for all cross-section conduits (Figure 13). Good agreement between the measured air demand ratio values and the computed air demand ratio values was obtained. If researchers use these equations, they will be able to determine the air demand ratio at the design stage without the need for experimental studies. This will provide researchers with great advantages in terms of both time and economy.

**CONCLUSIONS**

In this study, the effect of conduit cross-section geometry on air demand ratio was investigated. The results obtained are listed as items.

- The highest air demand ratio ($Q_a/Q_w = 4.71$) was observed in the circular conduit where the conduit length was 2 m and the gate opening ratio was 10%.

**Table 5 | Predictive equations for air demand ratio in different conduit cross-sections**

| Equation developed for 60 × 100 rectangular cross-section conduit | $Q_a/Q_w = 0.029(Fr - 1)^{0.881} \psi^{-0.125}$ | $R^2 = 0.90$ |
| Equation developed for 100 × 60 rectangular cross-section conduit | $Q_a/Q_w = 0.024(Fr - 1)^{0.809} \psi^{-0.039}$ | $R^2 = 0.85$ |
| Equation developed for circular cross-section conduit | $Q_a/Q_w = 0.014(Fr - 1)^{0.913} \psi^{-0.384}$ | $R^2 = 0.90$ |
| Equation developed for all cross-section conduits | $Q_a/Q_w = 0.026(Fr - 1)^{0.820} \psi^{-0.251}$ | $R^2 = 0.85$ |

where Fr: Froude number; $\psi$: gate opening rate; $h$: gate opening (m); $L$: conduit length (m); $R$: hydraulic radius (m).
It was observed that the conduit cross-section geometry did not have a significant effect on the air demand ratio at the gate opening rates greater than 10%.

In all conduit cross-sections, gate opening rates, and conduit lengths, the air demand ratio increased as the Froude number increased.

In all conduit cross-sections and conduit lengths, the air demand ratio decreased as the gate opening rate increased.

In all conduit cross-sections and gate opening rates, as the conduit length increased, the air demand ratio increased up to a certain value and then decreased. The highest air demand ratios were achieved in the conduit lengths of 2 m and 4 m.

The highest air flow rate was shown in the circular cross-section conduit for all gate opening rates and conduit lengths. However, since the water flow rate in the circular cross-section conduit was high, the air demand ratio decreased.

Regression equations with high correlation coefficients were obtained relating the air demand ratio to Froude number, gate opening rate, and ratio of gate opening to conduit length. These equations will provide a great convenience in estimating $Q_a/Q_w$ to designers.

The obtained results will be useful in future modeling processes and aid the practicing engineer in predicting air demand ratio for design purposes.

The primary purpose of water aeration is to increase the oxygen saturation of the water. This can be achieved by using hydraulic structures because of substantial air bubble entrainment at these structures. Closed conduit aeration is a particular instance of this. The experimental results showed that high-head conduits can be used efficiently in water aeration. Therefore, additional research is needed to better understand the effect of conduit cross-section geometry on oxygen transfer efficiency.

Great care must be taken when scaling results from models of two-phase flows as size-scale effects may exist. Previous studies have shown that the percentage of air entrainment was not affected by the size of the model. However, scaling of aeration data to prototype size is virtually impossible, largely due to the relative invariance of bubble size. Various model sizes may be necessary to determine the significance of size-scale effects of oxygen transfer efficiency in closed conduits between the different sized structures.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.
REFERENCES

Aydin, I. 2002 Air demand behind high head gates during emergency closure. *Journal of Hydraulic Research* **40** (1), 83–93.

Campbell, F. B. & Guyton, B. 1953 Air-demand in gated outlet works. In: *Proceedings of the Fifth IAHR Congress*, Minnesota, USA, pp. 529–533.

Dettmers, D. 1953 Beitrag zur Frage der Belüftung von Tiefschützen (A contribution to the problem of aeration of deep outlet gates). Mitteilung der Versuchsanstalt für Grund u. Wasserbau der Technischen Hochschule, Hannover, H-4.

Ervine, D. A. 1998 Air entrainment in hydraulic structures: a review. *Proceedings of the Institution of Civil Engineers Water, Maritime and Energy* **130** (3), 142–153.

Gongchun, C. & Chupei, Z. 1987 Some problems concerning two ways aeration in open pipe flow behind gates. In: *Proceedings of the 22nd IAHR Congress*, Lausanne, Switzerland, pp. 196–202.

Hager, W. H. & Bremen, R. 1989 Classical hydraulic jump: sequent depths. *Journal of Hydraulic Research* **27** (5), 565–585.

Hager, W. H., Bremen, R. & Kawagoshi, N. 1990 Classical hydraulic jump: length of roller. *Journal of Hydraulic Research* **28** (5), 591–608.

Haindl, K. & Sotornik, V. 1957 Quantity of air drawn into a conduit by the hydraulic jump and its measurement by gammaradiation. In *Proceedings of the International Association for Hydraulics Research*, Vol. 2, Lisbon, Spain, pp. D31.1-D31.7.

Kalinske, A. A. & Robertson, J. M. 1943 Closed conduit flow. *Transactions of the American Society of Civil Engineers, ASCE* **108** (1), 1435–1447.

Oveson, D. P. 2008 *Air Demand in Free Flowing Gated Conduits*. MSc Thesis, Utah State University, Logan, Utah.

Ozkan, F., Baylar, A. & Ozturk, M. 2006 Air entraining and oxygen transfer in high-head gated conduits. *Proceedings of the Institution of Civil Engineers-Water Management* **159** (2), 139–143.

Ozkan, F., Tuna, M. C., Baylar, A. & Ozturk, M. 2014 Optimum air-demand ratio for maximum aeration efficiency in high head gated circular conduits. *Water Science and Technology* **70** (5), 871–877.

Ozkan, F., Demirel, I. H., Tuna, M. C. & Baylar, A. 2015 The effect of length of free-surface gated circular conduit on air-demand ratio and aeration efficiency. *Water Science and Technology: Water Supply* **15** (6), 1187–1192.

Rajaratnam, N. 1962 An experimental study of air entrainment characteristics of the hydraulic jump. *Journal of the Institution of Engineers (India)* **42** (7), 247–273.

Shamsaei, A. & Soleymanzadeh, R. 2006 Numerical simulation of air-water flow in bottom outlet. *International Journal of Civil Engineering* **4** (1), 14–33.

Sharma, H. R. 1976 Air-entrainment in high head gated conduits. *Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers, ASCE* **102** (11), 1629–1646.

Speerli, J. & Hager, W. H. 2000 Air-water flow in bottom outlets. *Canadian Journal of Civil Engineering* **27** (3), 454–462.

Speerli, J. & Volkart, P. 1997 Air entrainment in bottom outlet tailrace tunnels. In: *Proceedings of the 27th IAHR Congress*, San Francisco, USA. Theme D, pp. 615–618.

Tullis, J. P. 1989 *Hydraulics of Pipelines: Pumps, Valves, Cavitation, Transients*. John Wiley & Sons, Inc., Canada.

Tuna, M. C., Ozkan, F. & Baylar, A. 2014 Experimental investigations of aeration efficiency in high head gated circular conduits. *Water Science and Technology* **69** (6), 1275–1281.

Unsal, M., Baylar, A., Tugal, M. & Ozkan, F. 2008 Increased aeration efficiency of high-head conduit flow systems. *Journal of Hydraulic Research* **46** (5), 711–714.

Unsal, M., Baylar, A., Tugal, M. & Ozkan, F. 2009 Aeration efficiency of free-surface conduit flow systems. *Environmental Technology* **30** (14), 1539–1546.

US Army Corps of Engineers 1964 Air-demand-regulated outlet works. In: *Hydraulic Design Criteria*. USACE, Chart 050-1.

Wisner, P. 1965 On the role of the Froude criterion for the study of air entrainment in high velocity flows. In *Proc. 11th IAHR Congress, Paper 1.15*, Leningrad. USSR.

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