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M.Sc. in Civil Engineering

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REPUBLIC OF TURKEY

GAZIANTEP UNIVERSITY

GRADUATE SCHOOL OF NATURAL & APPLIED SCIENCES

THE EFFECT OF THICKNESS INCREMENT ON THE CHARACTERISTICS OF WATER FLOW OVER SEMICIRCULAR WEIR

M. Sc. THESIS

IN

CIVIL ENGINEERING

BY

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Supervisor

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by

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This is to certify that we have read this thesis and that in our majority opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and proper conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Ali Fayeq SABER

ABSTRACT

THE EFFECT OF THICKNESS INCREMENT ON THE CHARACTERISTICS OF WATER FLOW OVER SEMICIRCULAR WEIR

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In this research, the hydraulic characteristics of the flow over the semi-circular weir with the semi-circular edge was investigated by laboratory experiments. For this purpose, 15 models were created. The models were tested in a laboratory flume 12 meters long, 0.80 meters wide and 0.90 meters deep.

The results showed that the relationship between the discharge and the other variables is a direct relationship and for all the used models but with varying percentages. Twenty-seven additional experiments were conducted for the purpose of determining the critical thickness. It was observed that the discharge started to decrease between the two thicknesses 1.2 cm and 1.6 cm. Through the experiments, it was obtained that the value of the critical thickness is 1.21 cm.

An empirical equation and simple application was developed in order to calculate the discharge (Q) over the semi-circular weir with semi-circular edge. This equation showed a very high correlation with the measured results.

It was found that the best value of the discharge over the semi-circular weir with semi-circular edge was obtained when the thickness was 1.2 cm and the radius of the weir's aperture was 25 cm.

Keywords: Semi-circular weir with semi-circular edge, Critical thickness, Dimensional analysis, Statistical analysis.

ÖZET

KALINLIK ARTIŞININ YARI DAİRESEL SAVAK ÜZERİNDEKİ SU AKIMININ KARAKTERİSTİKLERİ ÜZERİNDEKİ ETKİSİ

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Bu araştırmada, yarı dairesel kenarlı yarı dairesel savak üzerindeki akışın hidrolik özellikleri laboratuvar deneyleri ile incelenmiştir. Bu amaçla 15 model oluşturuldu. Modeller, 12 metre uzunluğunda, 0.80 metre genişliğinde ve 0.90 metre derinliğinde bir laboratuvar kanalında test edildi.

Sonuçlar, deşarj ile diğer değişkenler arasındaki ilişkinin doğrudan kullanılan bir ilişki olduğunu ve tüm kullanılmış modeller için ancak değişen oranlarda olduğunu göstermiştir. Kritik kalınlığın belirlenmesi amacıyla yirmi yedi deney yapılmıştır. Deşarjın 1.2 cm ile 1.6 cm arasında iki kalınlıkta azalmaya başladığı görülmüştür. Deneyler sırasında, kritik kalınlığın değerinin 1.21 cm olduğu belirlendi.

Yarı dairesel kenarlı yarı dairesel savak üzerindeki debiyi (Q) hesaplamak için deneysel bir denklem ve basit bir uygulama geliştirilmiştir. Bu denklem ölçülen sonuçlarla çok yüksek bir korelasyon göstermiştir.

Yarı dairesel kenarlı yarı dairesel savak üzerinde debinin en iyi değerinin, kalınlık 1.2 cm iken, savak açıklığının yarıçapı 25 cm olduğunda elde edilmiştir.

Anahtar Kelimeler: Yarı dairesel kenarlı yarı dairesel savak, Kritik kalınlık, Boyut analizi, İstatistiksel analiz.

To My Family

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My deepest appreciation went to my family in particular to my father who inspires me every day to strive for the best in my social and professional, and to my beloved mother for her pure and unconditional love, I appreciate immensely all of their support during my entire life. In addition, I would also thank my brothers, Mohammad, Ahmed, and my sister Raghad, they are who had always supported me in all aspects of my life through his words of wisdom and great guidance.

Special thanks to my friends, Really thank you from my heart for your supporting me and helping me in this period from my life.

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LIST OF SYMBOLS/ABBREVIATIONS

B	Weir's width
C	Coefficient of correlation
C_d	Coefficient of discharge
D	Diameter of pipe
d	Diameter of circular weir
Fr	Froude number
g	Ground acceleration
H	Total charge at the head of weir
$H_\circ$	water's height over weir
h_w	Water's height over peak of the weir
h_e	The height of water over weir's edge
L	the width of rectangular weirs
P	Height of weir's edge
Q	Flow discharge
Q_a	Actual discharge
q_w	Discharge / 1 m width.
R	Radius of weir
r	Radius of the weir’s top
R_1	Radius of the curvature in the parallel direction
R_2	Radius of the curvature in the vertical direction

Re	Reynolds number
$\mathbf{S_{\circ}}$	Slope of weir
T	Thickness of weir
V	Flow velocity
$\mathbf{V_{\circ}}$	Flow velocity mean
$\mathbf{y_1}$	Flow depth at the head of the weir
β	Angle of the back slope of the vertical and oblique weir
Ө	The angle of semicircular weir
$\mathbf{Ө_c}$	The central angle of circular weir is represented by a critical depth
ρ	Mass density for water
Ø	Angle of deviation of the weir from the channel wall
ϕ	The angle of v-notch
μ	Dynamic viscosity
η	Relative depth (H/D)

CHAPTER 1

INTRODUCTION

1.1 Preface

At the beginning of the 20th century the water resources have occupied a strategic importance for most countries in such a way that can surpass the importance of petroleum. Consequently, erecting or establishing hydraulic irrigation structure on rivers has increased to be used due to the lack in other resources and the difficulty to make use of it as well, such as underground water and rainwater.

Among such hydraulic structures are the weirs which were used previously to control the flow of water in so many water projects like dams, waterfalls of channels and water level regulators and the suppliers of the electric stations.[1]

1.2 General Overview about Weirs

Weirs are considered as one of the oldest hydraulic structures that man has ever erected on channels or rivers or can be defined is a barrier or obstruction in the open channel that arises in different types and forms on the width of the open channel or watercourse. Some traces have been discovered in the ancient ruins of many civilizations that inhabited on the earth, in which these weirs had been used in the open canals or gauging structures.

Then, these structures had been developed to build a less costly ones and more accurate in terms of easiness of gauging. Moreover, the flow equalizer for the weirs has been developed to be simpler as compared with the traditional weirs. Also, these weirs have become the most popular among the other preliminary means of gauging structure. In addition, the use of such weirs has been expanded in both projects and plans of water recourses.

Consequently, the simpler definition for the weir, is an obstruction in the open canal made up of multiple types along the width of open canal or the water stream and at the same time, reserves the water behind it and let it flow over it. This process makes the water flow in critically. In addition to what is mentioned above, most kinds of weirs and gauging structure techniques are used to perform a single duty. Generally speaking, the weirs are used for the following purposes:

1- Instrument for measuring water discharge in rivers as well as open canals.

2- Distributing the coming water from the major canals to the minor channels and in specific percentages.

3- Reducing water flow to minimize the damage brought about against the water structure. Therefore, they are used to dissipate the power of flow in areas with high slope of river.

4- Raising the water level in the canals for the purpose of irrigation and navigation.[2]

5- To be used as a passage for the extra water reserved in the reservoirs and ponds.

6- Obstructing the precipitations coming from the main stream of water.

7- Protecting against floods by disposing large quantities of water, especially in large weirs.[3]

1.3 Advantages and Disadvantages of Weirs

Advantages of weirs can be summarized in the main jobs and it is represented by the capacity to gauge large quantities of water accurately, the easiness of structuring and installing, the capacity of use collectively to be combined with other structures and the capacity of transformation as compared with small weirs.

But the disadvantages of weir are : It require a relative height of water especially for the free flow and this in turn precludes the practical use of them to gauge the flow in the flat areas and the weirs collect sediments and suspended materials coming from the watercourse in addition The front pool of the weir (U/S) should be clean of precipitations, litters and pond weeds because these can fail the level of accurate gauging. Finally They cause an erosion at the rare part of the structure (D/S).[4]

1.4 Classification of Weirs

Weirs can be classified to different types according to their shapes (the shape of the opening or fissure) such as the rectangular, triangular and trapezoidal etc.

Figure 1.1 – 1.4 represent different shape for weirs. Similarly, these weirs are with a broad crest or sharp crest but most of them that are used to gauge the discharge are thin thickness.[3]

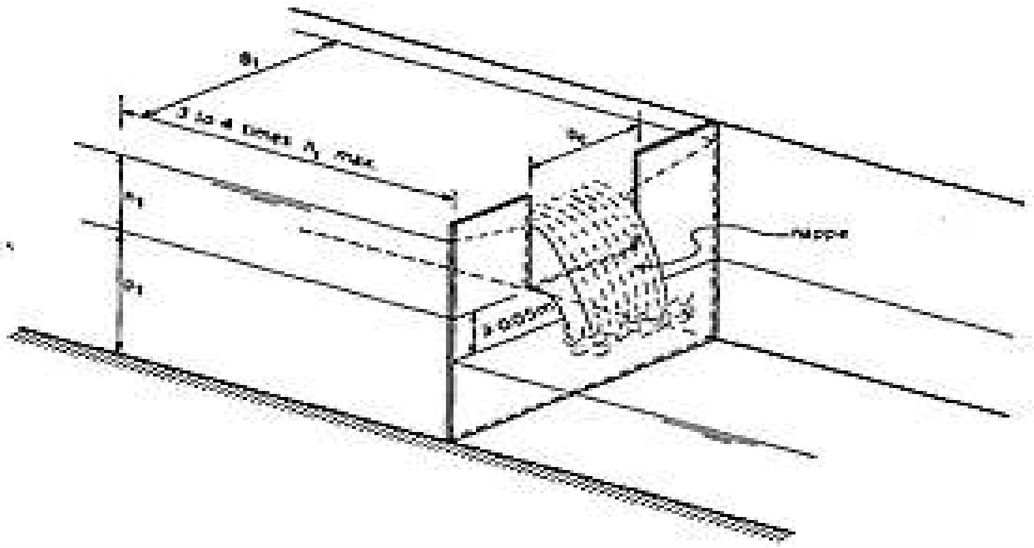

Figure 1.1 Rectangular weir with sharp crest

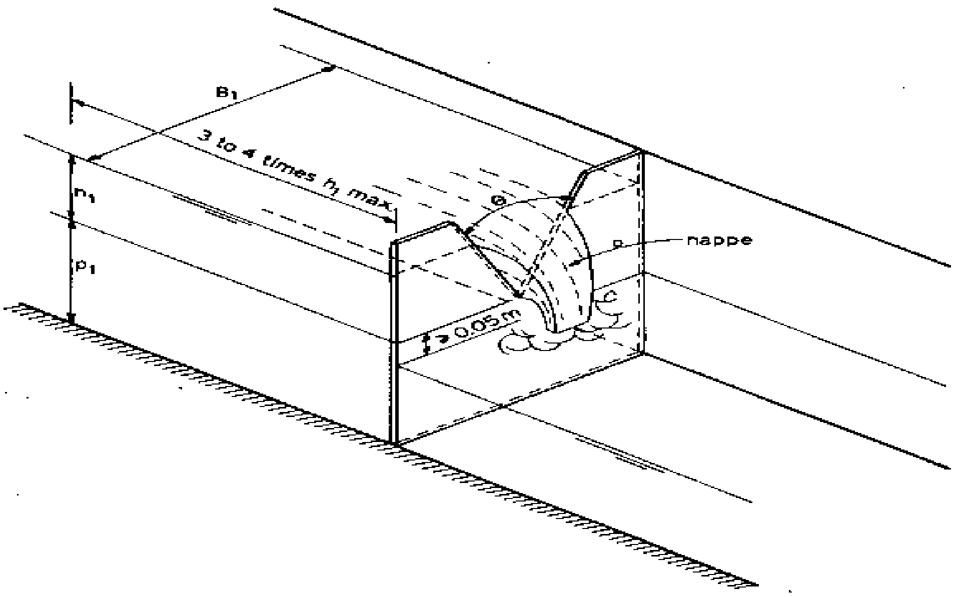

Figure 1.2 V-notch weir with sharp crest

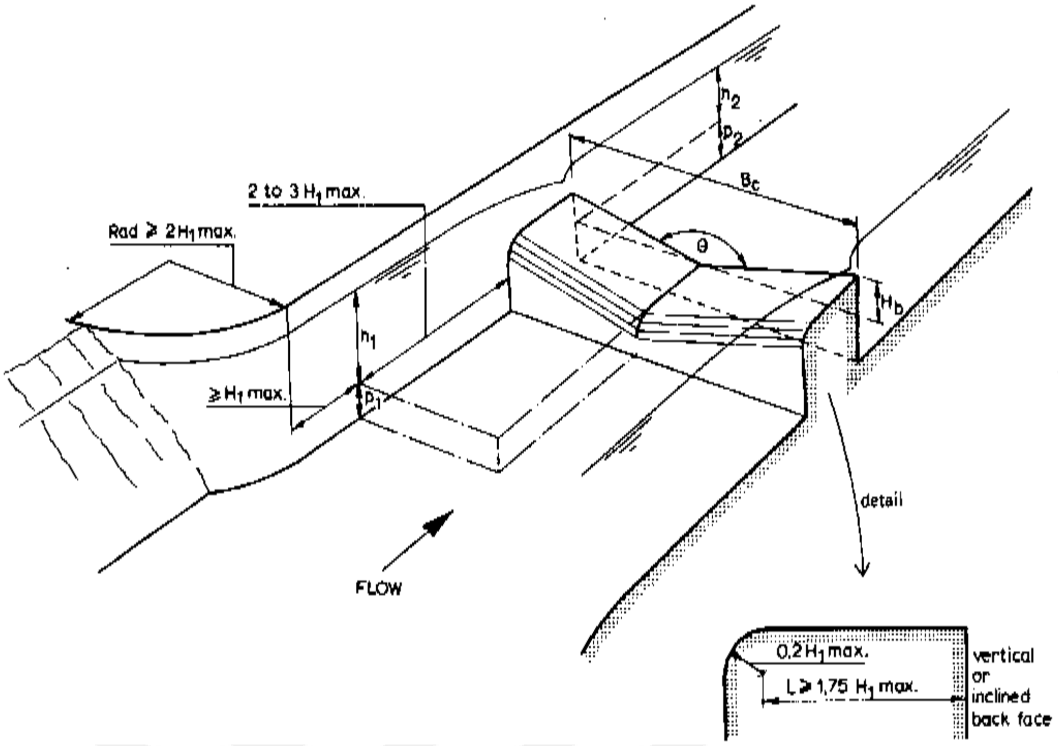

Figure 1.3 Traingular weir with broad crest

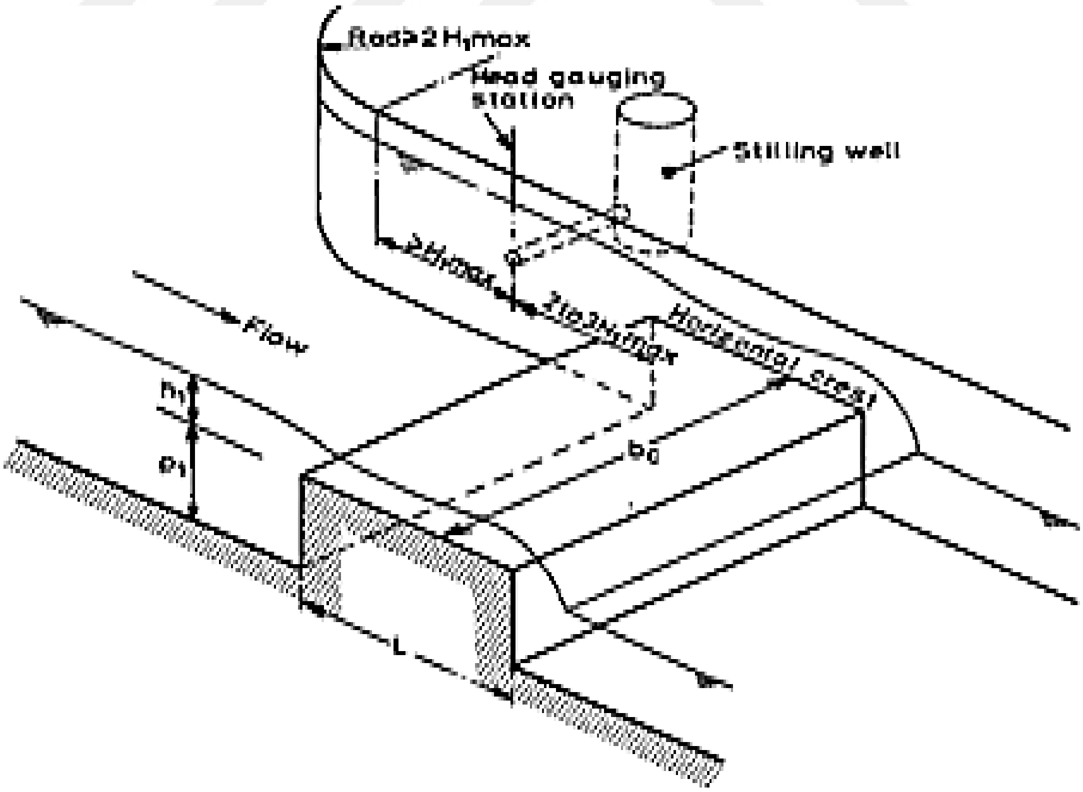

Figure 1.4 Rectangular weir with broad crest

1.5 Types of Weirs with a Thin Thickness

Weirs with a thin thickness can be classified as follows:

1- Straight weirs with a width as same as the width of canal's section and their passage is of rectangular shape and they are placed on the wall of the canal itself prependicularly.

2- Straight weirs in which their cross section is of a rectangular shape but their width less than that of any canal where a contraction occurs in the canal for these weirs. They are also called the rectangular weirs with a narrow section and their upper edges may be acute or semicircular and they are used for the following purposes:

   - To reduce the canal’s width.
   - To accelerate the flow in the canal.
   - To supply the required air ventilation for passing the flow over the weir.

   In general way the rectangular weirs are used in the canals which have large discharge within a range of wide operating.

3- Weirs with a triangular section (V-notch) and they mostly used in the canals with less discharges within a range of narrow operating which means they give accurate gauging of the less flowing water and the lower angle for this weir is 90 and other angels can be used in the design itself.

4- Weirs with a trapezoidal manhole and they actually used in improving the rectangular weir with a higher capacity of the same peak and this manhole is about (4 Vertical) to (1 Horizontal).

5- Weirs with special shapes which are less popular as compared with those previously mentioned such as the acute as the upper sight triangular and the combined weirs (i.e. they are a mixture of the previous ones). These combined weirs are used in formulating a specific site or in achieving a relation of discharge or a specific water quantity.[4]

Despite many studies carried out on weirs with a sharp-crested weirs there still less studies that emphasize the circular weirs or semicircular ones with a circular sharp-crest weirs. The circular or the semicircular weir can be defined as a circular control cross lies in the vertical thin plate.

1.6 Objective and Aim of The Thesis

According to the gained results from experimental work for semicircular weirs, the current study aims to:

1- Study the characteristics of flow over semicircular weirs with a semicircular edge.
2- Study the factors connected with semicircular weirs such as studying the influence the weir's thickness on the level of discharge passes over there weirs, the radius of the weir, the edge's height of the weir, in addition to depth of water over the edge of the weir.
3- Conclude an emprical relations to calculate the quantity of the discharge of flow over the semicircular weirs depending on the impacting factors in this discharge by using the theory of dimensional analysis and the two programs statistics program SPSS and Minitab.
4- Identify the critical thickness of the weir in which the change of discharge depends on it , any increment or decrement occurs.

1.7 Limitation of The Study

In the current study, an identification of the hydraulic characteristics of semicircular with semicircular-crested weirs will be acknowledged via analyzing experimental findings on samples with radii and different heights and thicknesses. The general limitations for this study are:

1- All the values and records specified with this work that have been gained from experiments in specialized labs with high efficiency .
2- It was ascertained that all experiments that resulted the obtained values in this study were subject to all the conditions and special criteria for such work.
3- Comparing the concluded findings with previous studies in the same field to prove the accuracy of the gained and used values in this study respectively.

1.8 Layout of The Thesis

This thesis consists of five chapters which can be summarized as follows:

Chapter One includes general introduction, advantages and disadvantages of weirs, classification and types of weirs and objective of the present study.

Chapter Two contains the literature review of previous researches about the experimental study of different weirs.

Chapter Three explains methodology of the study and the experimental setup.

Chapter Four presents the description and discussion of the results.

Chapter Five presents the general conclusions of this research and also some recommendations for future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The main aim of diving dams studies is to find a constant relationship between the discharge for these facilities and the depth of it's peak.[5,6]

But this relationship deviates from the correct estimation for the following reasons:

1- The roughness of canal bottom.
2- The canal bottom effects by sedimentation and undercutting.
3- The effect of canal rear.
4- The relationship sedimentation and the depth in the level of flood depends on the spread of flood.
5- The relationship between sedimentation and depth is not stable in the low level depths.[6]

The empirical formula to count the amount of water in all the canals and rivers are used and then the derivational math are used. The formulas are put to count the sedimentation for the submersible dams and the sewerage disposal through the other irrigation structure.[7]

This chapter includes some researchers and previous studies that are specialized in the studies of the characteristics of flow over the submersible dams in the rivers and canals.

The majority of studies depends on the laborites results of experiments where in the submersible with their different shapes are used to measure the discharge disposal over them by considering them as structures of over flow to control the water level in the canals and tanks.

2.2 Previous Studies

Weirs studies had attracted many researchers since the 18th century, and the formula was first put by Polini (1717), for the rectangular submersible weir as in the following:

$$Q = \frac{2}{3} * C_d * \sqrt{2g} * B * h_w^{\frac{3}{2}} \tag{2.1}$$

Where, C_d is the factor of discharge, g is ground acceleration, B is the width of weir. h_w is the height of water over the peak of the weir.[8,9]

Weisbach (1846), studies the influence of the speed of water over the surface of the weir. He develops the formula of Polini by adding the average of the speed and the formula is now:

$$Q_{act} = \frac{2}{3}\, C_d\, \sqrt{2g}\, B[\left(h_w + \frac{{v_o}^2}{2g}\right)^{\frac{3}{2}} - (\frac{{v_o}^2}{2g})^{\frac{3}{2}}] \tag{2.2}$$

Where, v_o represents the speed average for the flow that comes from the front of the weir.[8,9]

Francis (1852), has carried out several lab experiments on different samples of weirs and has concluded this formula, as shown below:

$$Q = \frac{2}{3} C_d \sqrt{2g} L (H + \frac{{V_a}^2}{2g})^{1.5} - (\frac{{V_a}^2}{2g})^{1.5} \tag{2.3}$$

Where, V_a = the average flow (m/s).

In this formula, the researcher has used different lengths of the weir L in his experiments which ranged between 1.07 - 5.19 m with a height of water over the weir H equal 0.18 and 0.49 m.[10]

Through the study, it has been concluded that the coefficient of discharge C_d under these factors is 0.622 with disregard of the speed change, the discharge formula will be as follows:

$$Q = 1.48 * L * H^{1.5} \tag{2.4}$$

Mathew (1968), has carried out several experiments on different samples of weirs with circular edges by using different radii and has concluded that the surface tension and the water's viscidity and the geometrical dimensions of the weir especially in the smaller samples. All this has occurred because of the effect of the scale effect's factor (scale effect) in which in the low value H/r and has suggested the following formula to calculate the discharge coefficient:

$$C_d = 0.385 * \left[1 + \text{a}\left(\frac{H}{r}\right) - \text{b}\left(\frac{H}{r}\right)^2 - \text{c}\left(\frac{r}{H}\right)\right] \quad (2.5)$$

Where, a, b and c are the constants depending on the weir's shape, H is the height of water over the weir's edge, r = the radius of the weir's top.[11]

Abid Ali (1989), has applied a method of finite elements to study the characteristics of the flow over the semi-cylindrical weirs or the arch-harp form. These weirs have been placed vertically on the flow's sector and this study has been carried out using different samples of weirs with different rates of height from the base and as shown in the Figure 2.1.

The discharge coefficient has been found to represent the mark of the dimensions of the weir and the magnitude of water at the forefront side of the weir. Then, the following formula has been set to calculate this coefficient:

$$C_d = 0.419 * \left(\frac{H}{P}\right)^{0.102} * \left(\frac{R}{P}\right)^{0.019} \quad (2.6)$$

Where, R = the radius of weir's peak.

The researcher has concluded that the weir's discharge with the semi-cylindrical edge is bigger than the weir with the sharp edge.[12]

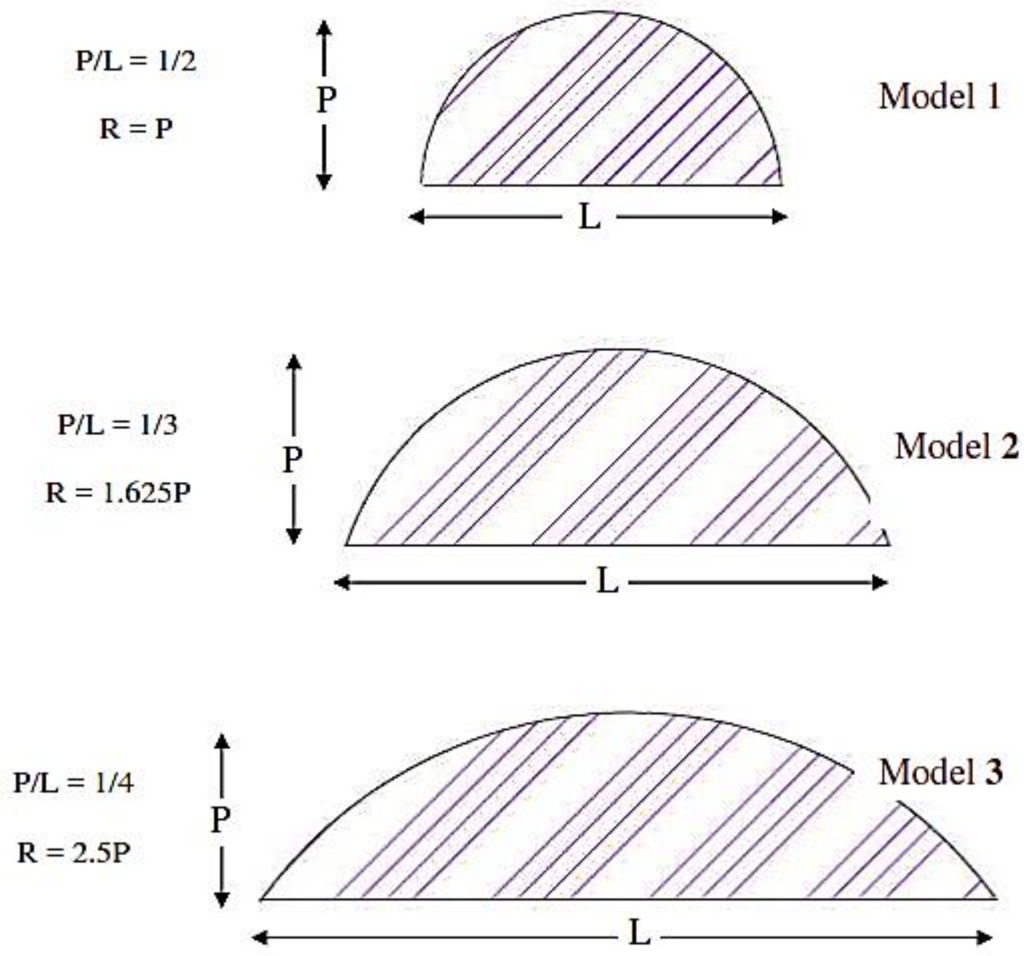

Figure 2.1 The used models by Abid Ali (1989)

Stevens, as mentioned in Boss (1989), has derived a formula for the weirs with a cylindrical hole that connects the theoretical discharge with the height of the water in a form of an oval integrity of the first and the second type. This formula is so complicated and unsuitable for practical purposes, therefore, Stevens has modified it.

Though some researchers have calculated formulas of theoretical discharge of the functional relationships between the height of the water and the theoretical discharge of the weirs with a cylindrical hole and a sharp edge, so many modifications need to be done for such formulas to gain the acceptable accuracy.[13]

Balachander et al. (1991), have represented a simple way to calculate the coefficient of the discharge for the cylindrical weirs with a sharp edge and a light thickness. The given sample has proved its accuracy by using the experimental data for the practical side which is faced in the field and a simplified formula to calculate the coefficient for the discharge of the weir.[14]

Ramamurthy and Diep (1994), have conducted an experimental study on the characteristics of flow over the weirs with circular edge.

The experiments have been carried out to show the influence of the slope of the weir's frontier on the coefficient of discharge (C_d), where the slope (Ø) has been changed to three times (60, 75 and 90), and the slope of the rear (β) into three times (45, 60 and 75), and after analyzing the findings, those researchers have concluded the following:

1- When the slope of the weir's frontier is Ø = 90 and the rear's slope β= 45 so the discharge coefficient (C_d) decreases till it reaches its value in the weirs sharp edge and this happens when increasing the height rate of water over the weir to the radius of the top H/r of 5.5 .

2- The influence of the slope of the weir's frontier over the discharge coefficient (C_d) is less when fixating the shape of the weir's rear, whereas fixating the weir's frontier at $H/r > 5$ so the value (C_d) increases when increasing the slope of the weir's rear.[15]

While Chilmeran (1996), has studied the flow's characteristics over the vertical oblique weirs with a semicircular crest under cases of free flow experimentally. In this study, 48 samples have been constructed and examined in which the first 12 samples have been used with the vertical weir while the rest of the samples were oblique of the weir's central line. Figure 2.2 explains one of the used samples in this study.

The researcher has concluded the following:

1- The discharge coefficient (C_d) for the vertical weir increases according to the increment of the depth of water over the weir's crest to the height of the crest (H/P).

2- The crest with a circular crest achieves better performance as compared with the one of the sharp edge for all heights and for all the radii of the weir's edge used in the study.

3- The following formula has been concluded to calculate the discharge coefficient.

$$C_d = \frac{0.579}{(\frac{H}{p})^{0.17} * (\frac{r}{p})^{0.61} * \sin \emptyset^{0.87}} \quad (2.7)$$

Where, Ø = the channel's deviation corner.[16]

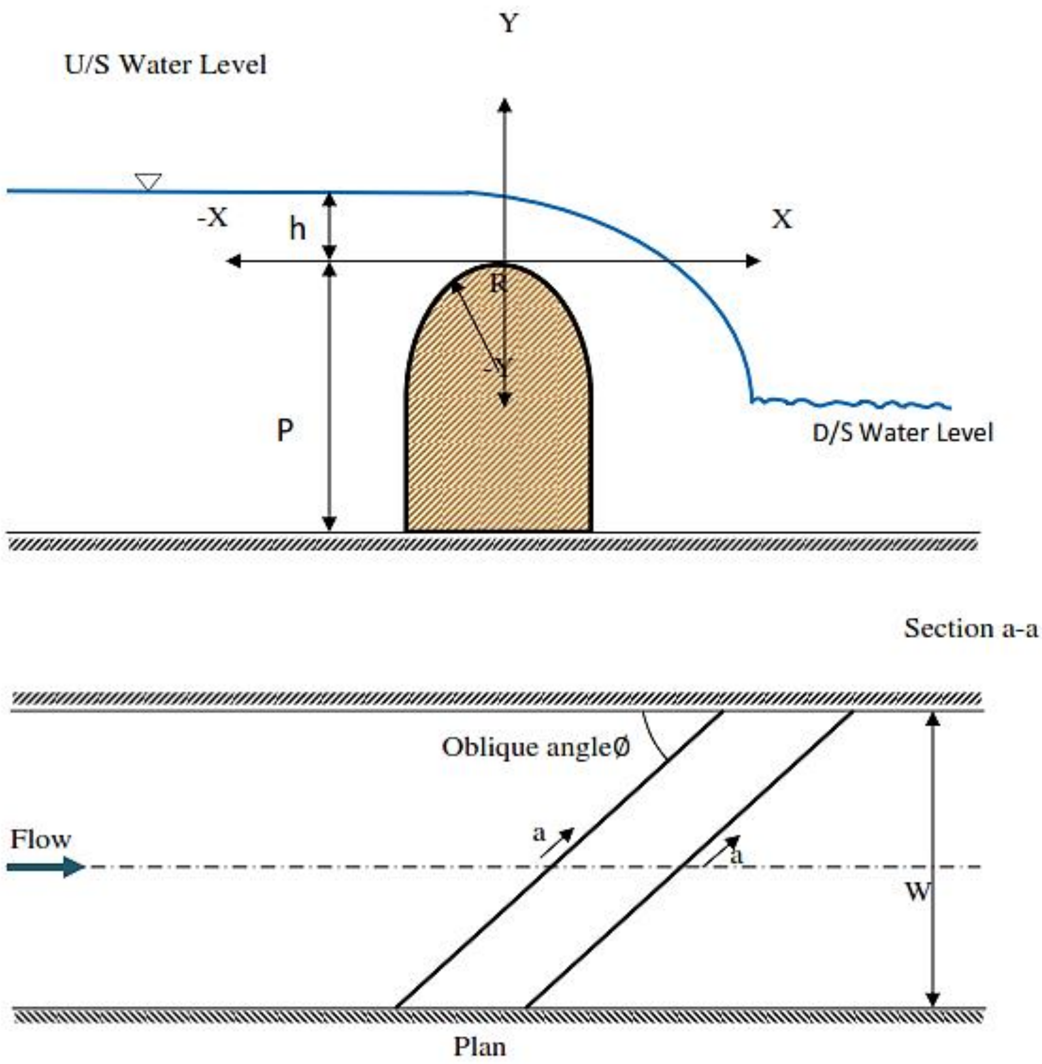

Figure 2.2 The used models by Chilmeran (1996)

Noori and Hayawi (1996), have carried out a study on the diving dams of radius zigzag vertically and a slope edge in a convex and a concave form with the direction of the flow. 12 samples have been examined in which the first 6 with 15 cm radius, while the other 6 were with 7.5 cm and these samples were having three different heights (P = 10, 15 and 20 cm).[17]

The following conclusion has been made as :

1- When the depth of the water over the weir's edge increasing with regard to the weir's edge (H/P), both the discharge coefficient and the performance decreases, though the discharge coefficient of the concave samples is bigger than the discharge coefficient of the arched sample.

2- The low weir's performance is better than the high one's.

3- The two following formulas has been concluded to calculate the discharge coefficient:

For concave figure:

$$C_d = 0.49 * \frac{\left(\frac{R}{P}\right)^{0.11}}{\left(\frac{H}{P}\right)^{0.24}} \tag{2.8}$$

For convex figure:

$$C_d = 0.49 * \frac{\left(\frac{R}{P}\right)^{0.3}}{(\frac{H}{P})^{0.1}} \tag{2.9}$$

Chauson and Montes (1998), have studied the characteristics of cylindrical skimmers. This study has included the use of different volumes of cylindrical weirs with different heights. It has been concluded that the size of the cylinder and the total rate of the weir's height to the radius P/R along with the influence of the existed slope at the frontier of the weir which does not affect the discharge coefficient.[18]

The following relation has been derived to calculate the discharge **:**

$$q_w = \frac{2}{3} C_d * \sqrt{g} * H^{\frac{3}{2}} \tag{2.10}$$

Al-Tikrity (2000), studied the hydraulic characteristics of the vertical weir with a semicircular edge in the laboratory under free flow conditions. The researcher also compared the results obtained from the study of this type of weirs with the sharp-edged weirs under the same flow conditions through the discharge coefficient and the form of the water surface and their performance in passing the discharges. The results showed that for the same percentage of water depth over the weir to the height of the weir (H/P), the discharge coefficient (C_d) of the semi-circular weirs is greater than the discharge coefficient for sharp-edged weirs 9.67% - 20.92%. The values of C_d increased with the increase of the diameter of the peak to the height of the model (r/P) for the same ratio (H/P). The results concluded that the flow of the flow near the peak is greater in the semi-circular edge models than in the sharp-edge models.[10]

The researcher Hayawi (2004), studied the effect of the downstream inclination of vertical and oblique weir with semicircular peak under laboratory free flow conditions. In this study, 45 samples were constructed and tested, with the models divided into several different groups depending on the angle of deviation Ø with the channel wall equals (90°, 60°, 45°, 30° and 25°), and the back slope equals (75°, 60° and 45°), and three heights (10, 20 and 30 cm). The results of the study showed that the surface forms of the water were smooth and continuous flow down and then began to fall sharply down the path of the slope of the back of the vertical weir. It was also observed during the study that the performance of semi-circular top weir is better than sharp-edged weir and for all values of the height and slope of the rare of weir used in the study. It was found that the discharge coefficient of the vertical weir increased by increasing the water depth ratio to the height of the vertical weir H/P and by increasing the back inclination of all models and all heights. Vertical heights with low heights 75° give higher values than those with high altitudes 20 and 30 cm. In the case of oblique weirs, the coefficient of discharge decreases by increasing the depth of the water to the height of the oblique weir H/P of all models and for all heights.[19]

There was also a general relationship obtained to calculate the discharge coefficient C_d for this type of weirs and as follows:

$$C_d = 0.7883 * \left(\frac{H}{p}\right)^{0.01748} * (sin\emptyset)^{0.5131} * (\beta)^{0.3127} \quad (2.11)$$

Where, $\emptyset$ = Angle of deviation of the weir from the channel wall, β = Angle of the back slope of the vertical and oblique weir.

Rahim et al. (2004) studied and compared the hydraulic properties of the weir, circular and semi-circular weir under the free and submersible flow conditions. In the study, eighteen different models were used. The first nine models were circular. The rest of the models were semi-circular and had the same dimensions as the following table:

Table 2.1 Models dimension used by Rahim et al. (2004)

Group N0.	Crest Radius r(cm)	Crest Width B(cm)	Crest height P(cm)
A	3	8.6	12
			14
			16
B	4	8.6	12
			14
			16
C	5	8.6	12
			14
			16

The results showed that the height of the model P, the height of the water over the weir h_1, the ratio h_2/h_1, and the slope of the channel have an effect on the discharge coefficient C_d. The results showed that the discharge coefficient of the weirs was greater than the semi-circular models under the free and submersible flow conditions. The values of the discharge coefficient C_d of the submerged flow of both circular and semi-circular weirs are lower than in the case of free flow by ratio about 1 - 15%.[20]

Vatankhah (2010), used the experimental data and presented a simple and accurate equation for the theoretical discharge of the sharp-edged circular weirs. The maximum error ratio in this equation compared with the accuracy results of numerical integration was less than 0.08%, and by using the empirical data also the researcher presented an equation to calculate the discharge coefficient of these weirs. Thus, real (actual) discharge can be calculated by the following proposed equations:

$$C_d = \frac{0.728 + 0.240\eta}{1 + 0.668\sqrt{\eta}} \quad (2.12)$$

$$Q_a = 0.3926 C_d \sqrt{2g} H^{3/2} * D * \eta^{\frac{1}{2}} * \left(\sqrt{1 - 0.2200\eta} + \sqrt{1 - 0.7730\eta}\right) \quad (2.13)$$

Where, C_d is the coefficient of discharge, η: relative depth H/D, Q_a is the actual discharge, g is the gravitational acceleration equal to 9.81 m/sec^2, H is the flow depth over edge of weir, D is the diameter of circular sharp - edged weir.[21]

The researcher Ghadban (2011), studied the hydraulic characteristics of the sharp-edged with semi-circular opening. The study was based on the dimensional analysis assisted by the laboratory work. The results of the dimensional analysis showed that the factors influencing the discharge above this type of weirs are the ratio depth of the flow over the weir to the radius of weir's opening H / R and the flow depth over the weir to the height of the weir edge H/P. Laboratory experiments were carried out on 16 models of semi-circular weirs, where the radius was changed four times (5, 10, 15 and 20 cm), and each radius the height of weir edge was changed four times (15, 20, 25 and 30 cm). The results showed significant effect of H/R coefficient on the discharge coefficient $\frac{Q^2}{g*H^5}$, while the effect of the H/P coefficient was limited. The statistical program SPSS was used to devise an empirical equation for the calculation of the discharge over the semi-circular weir by depending on the non-dimensional factors and laboratory results as follows:

$$\frac{Q^2}{gH^5} = \emptyset_4\left(\frac{H}{P}, \frac{H}{R}\right) \quad (2.14)$$

The results of the equation showed a significant correlation with the laboratory results in finding the amount of discharge by the depth of the flow over the weir H, the cutting radius of the weir hole H and the height of the weir edge P. The results also showed the large effect of the aperture diameter on the discharge magnitude over the weir and the low effect of the height of the edge of the weir on this discharge.[22]

The researcher Mohammed Ali (2012), studied the hydraulic properties of oval-shaped weir with sharped edge, and in his study he depended on the dimensional analysis of the extracted laboratory results. It was found that the factors influencing discharge over ovals weir with a sharp edge are the ratio between the small radius of the oval shape and the height of the water above the weir a / H and the ratio between large radius of the oval shape to the water height above the edge of the weir b / H and the ratio between the height of the weir and the water above the weir P / H, where 12 samples were used by changing the smaller diameter four times b = 2a and b = 1.5a where a = 5cm and a = 2b, and a = 1.5b where b = 5cm and also the change in the height of the weir three times 10, 20 and 30 cm.[23]

The following equation was inferred to calculate the value of discharge over this type of weirs:

$$Q = 0.023 * \sqrt{g} * H^{2.5} * \frac{(\frac{a}{H})^{0.403} * (\frac{b}{H})^{0.37}}{(\frac{P}{H})^{0.055}} \tag{2.15}$$

Ghobadian and Meratifashi (2012), studied the relationship of the theoretical discharge phase of the circular weirs with the sharp edge, assuming the occurrence of critical flow over the edge of weir, and the study solved two of the nonlinear equations extracted to study the accuracy of the theoretical discharge phase as shown in the following equations:

$$Q = C\left[\frac{g[\frac{D^2}{8}(\Theta_c - \sin\Theta_c]^3}{D\sin\left(\frac{\Theta_c}{2}\right)}\right]^{\frac{1}{2}} \tag{2.16}$$

$$H = \frac{D}{2}\left(1 - \frac{\cos\Theta_c}{2}\right) + \frac{D}{16}\left[\frac{\Theta_c - \sin\Theta_c}{\sin\left(\frac{\Theta_c}{2}\right)}\right] \tag{2.17}$$

Where, Q is the flow discharge, Θ_c is The central angle of circular weir is represented by a critical depth, g is the gravitational acceleration, D is the diameter of circular weir, H is the total charge at the head of weir.

58 experiments on 6 circular weirs with different diameters and different heights of the edge. The results show that the phase of theoretical discharge calculated above the weir is less than the measured discharge. This difference increases with the

phase. The theoretical discharge phase relationship was modified through the use of the correction coefficient, which is an equation of the depth of the flow at the head of weir to the height of the edge of the weir and as shown in the following equations:

$$C = \cos\left[\frac{\frac{y_1}{p} + 6.46289}{(\frac{y_1}{p})^3 - 1}\right] + \tan^{-1}[\frac{-2.293426}{\frac{y_1}{p}} + 3\frac{y_1}{p}] \quad (2.18)$$

$$Q = C\left[\frac{g[\frac{D^2}{8}(\Theta_C - \sin\Theta_c]^3}{D\,sin\left(\frac{\Theta_c}{2}\right)}\right]^{\frac{1}{2}} \quad (2.19)$$

Where, C is the coefficient of correction, y_1 is the flow depth at the head of the weir, P is the height of weir's edge.[24]

The results show that the modified discharge phase relationship is in good condition and is consistent with the measured results as shown in Figure 2.3.

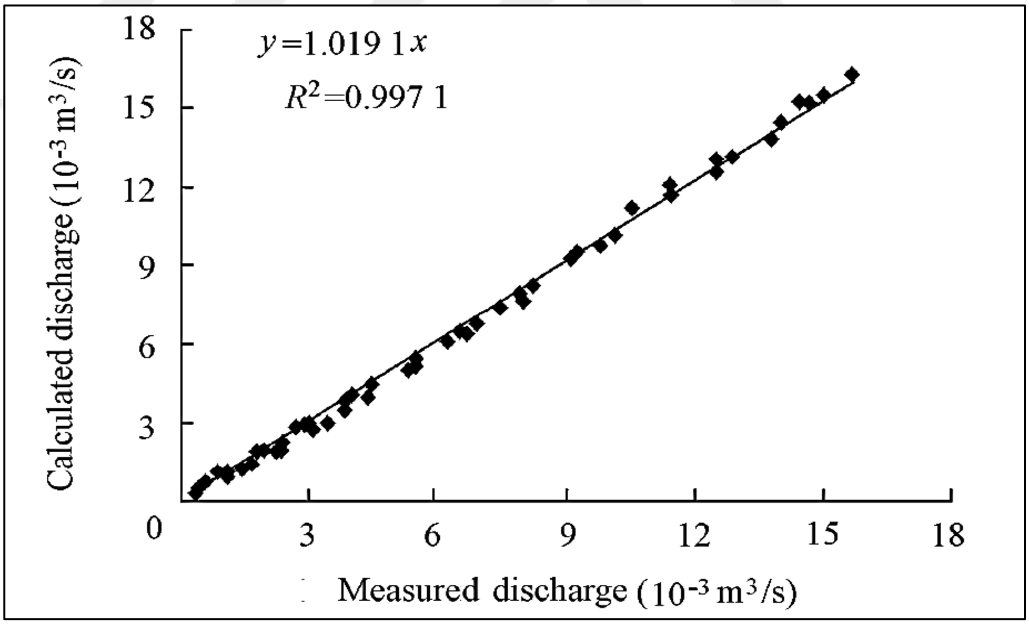

Figure 2.3 Relationship between measured discharge and discharge calculated from Equation 2.19

Al-Mousawi et al. (2013) conducted a study to calculate the discharge coefficient of semicircular notch weirs, where the semi-circular models were made with different diameters 6,8 and 10 cm, and the models were used by using the hydraulic table in the laboratory in the same conditions in terms of temperature and several times,and they are intended for all models of a notch with section (rectangular, triangular and semi-circular). To determine the best shape for the notch of weir, take the C_d as a function, and the discharge coefficients of the three segments can be calculated using the following equations:

1. Equation of the discharge coefficient of rectangular weirs:

$$C_d = \frac{Q}{\left(\frac{2}{3} * \sqrt{2g} * L * h^{\frac{3}{2}}\right)} \tag{2.20}$$

2. Equation of the discharge coefficient of triangular weirs:

$$C_d = \frac{Q}{\left(\frac{18}{5} * \sqrt{2g} * \tan\frac{\phi}{2} * h^{2.5}\right)} \tag{2.21}$$

3. Equation of the discharge coefficient of semi-circular weirs:

$$C_d = \frac{Q}{\left(\sqrt{2gh} * \left(\frac{d^2}{16(\Theta - \sin\Theta)}\right)\right)} \tag{2.22}$$

Where, Q is water discharge, C_d is the discharge coefficient, g is gravitational acceleration, h is the water's height over weir, L is the width of rectangular weirs, d is the diameter of weir, ϕ is the angle of v-notch, Θ is the angle of semicircular weir.

When the results were observed, found that the values of the discharge coefficient C_d for rectangular notch ranges between 0.71 - 0.73, while the discharge coefficient C_d for triangular notch ranges between 0.78 - 0.89, while the discharge coefficient C_d for the semi-circular notch, it ranges between 0.88 - 0.93.[25]

Al-Jubouri (2013), carried out a laboratory study to determine the hydraulic characteristics of the flow over the arched weirs with the sharp and semi-circular edge. Four values were used for curvature ratio R_1 / R_2 equals 0.5, 1, 2 and 4, where R_1 represents the radius of the curvature in the parallel direction of the flow and R_2 the radius of the curvature in the vertical direction on the flow as shown in the following form:

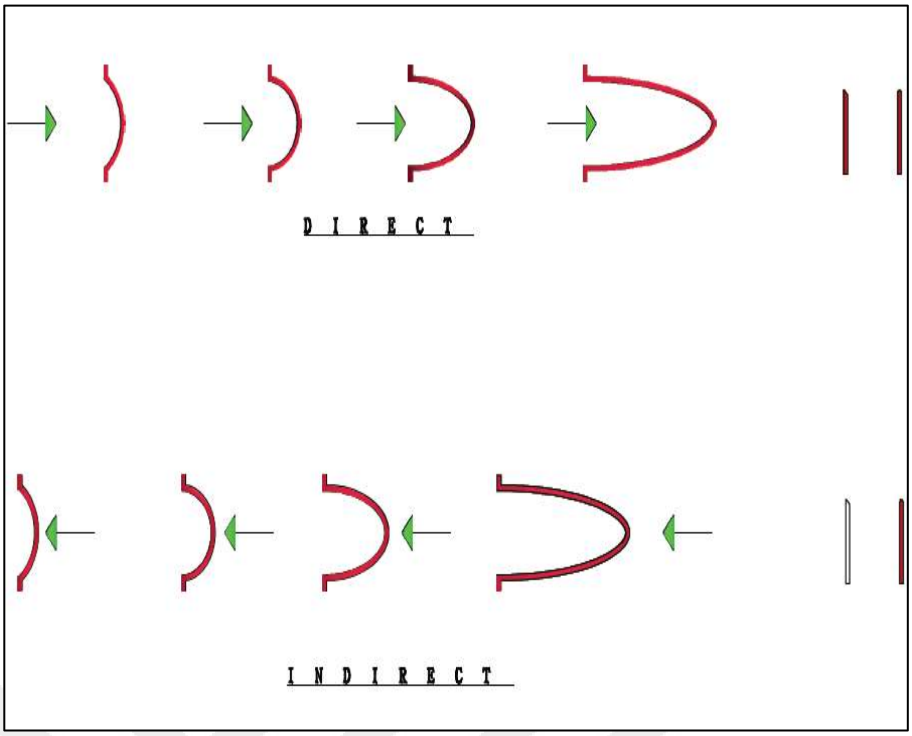

Figure 2.4 The used models by Aljubouri (2013)

Three heights P were used for each of these weirs (15, 18 and 22 cm). The flow passed over these weirs in two cases the first where the curvature is directed toward the flow and the second is the curvature opposite the flow direction. For each of these cases, six different discharges were carried out, where the number of experiments conducted on this type of weirs 288 experiments.

Through of the gained results from these experiments and based on the derived coefficients from the dimensional analysis of the factors affecting the flow over this type of weir, the relationship between these coefficients was plotted.

The results showed a positive correlation between the coefficient $(\frac{Q}{H_{\circ}^{5/2} * g^{1/2}})$ and the height of the edge of the weir to the depth of the water above its edge $\frac{P}{H_{\circ}}$ and for all the flow cases above, Alsothe results showed that for the same ratio $\frac{P}{H_{\circ}}$, the coefficient $(\frac{Q}{H_{\circ}^{5/2} * g^{1/2}})$ increases with the increase of the ratio of curvature $\frac{R_1}{R_2}$, where Q represents the discharge over the weir and g represents the gravitational acceleration.

In addition, the results showed that the coefficient ($\frac{Q}{H_\circ^{5/2} * g^{1/2}}$) increases with the increase of $\frac{R_1}{H_\circ}$ and for all the flow conditions. At a certain ratio of $\frac{R_1}{H_\circ}$, The value of the coefficient ($\frac{Q}{H_\circ^{5/2} * g^{1/2}}$) decreases with the increase of the curvature ratio $\frac{R_1}{R_2}$. The results also showed that the coefficient ($\frac{Q}{H_\circ^{5/2} * g^{1/2}}$) increases with the increase $\frac{R_2}{H_\circ}$ and for all flow cases. At a certain ratio of $\frac{R_2}{H_\circ}$, The value of the coefficient ($\frac{Q}{H_\circ^{5/2} * g^{1/2}}$) increases with the increase of the curvature ratio $\frac{R_1}{R_2}$.

Four empirical equations have been devised to calculate the discharge over curved weirs and for the following cases:

1-The discharge equation for the sharp and arched edge with the flow direction:

$$Q = 1.566 * H_\circ^{\frac{5}{2}} * \sqrt{g} * \left(\frac{P}{H_\circ}\right)^{-0.066} * \left(\frac{R_1}{H_\circ}\right)^{0.681} * \left(\frac{R_2}{H_\circ}\right)^{0.506} \quad (2.23)$$

2- The discharge equation for the sharp and arched edge with reverse the flow direction:

$$Q = 1.480 * H_\circ^{\frac{5}{2}} * \sqrt{g} * \left(\frac{P}{H_\circ}\right)^{0.089} * \left(\frac{R_1}{H_\circ}\right)^{0.520} * \left(\frac{R_2}{H_\circ}\right)^{0.652} \quad (2.24)$$

3- The discharge equation for the sharp and semicircular edge with the flow direction:

$$Q = 1.722 * H_\circ^{\frac{5}{2}} * \sqrt{g} * \left(\frac{P}{H_\circ}\right)^{-0.042} * \left(\frac{R_1}{H_\circ}\right)^{0.610} * \left(\frac{R_2}{H_\circ}\right)^{0.556} \quad (2.25)$$

4- The discharge equation for the sharp and semicircular edge with reverse the flow direction:

$$Q = 2.044 * H_\circ^{\frac{5}{2}} * \sqrt{g} * \left(\frac{P}{H_\circ}\right)^{-0.680} * \left(\frac{R_1}{H_\circ}\right)^{0.745} * \left(\frac{R_2}{H_\circ}\right)^{1.144} \quad (2.26)$$

These equations showed a very good correspond between the obtained results from these equations and the measured results practically.[4]

Irzooki et al. (2014) also conducted a laboratory study of the characteristics of the flow over weirs with the semi-circular aperture. Four radii were used for the aperture of the weir. For each aperture, three heights were used for the edge of weir, and two cases, one of it with the sharp edge, and the other with the semi-circular edge.

The results showed that for the same height of the edge of the weir and for the same depth of water over the edge, the discharge of the water above the weir increases with the increase radius of the weir's aperture. It was also observed that for the same radius of the weir's aperture and for the same depth of water over the edge of the weir, discharge of the water over the weir increases with the increase of the height the weir's edge. It was also found that the discharge passing over the weirs with semi-circular edge is more than in the weir with sharp edge and to the same flow conditions. To measure the discharge over the weirs with semi-circular apertures, a reliable empirical equation was found for the semi-circular weirs with the sharp edge and as follows:

$$Q = 0.762 * H_{\circ}^{2.5} * \sqrt{g} * \left(\frac{P}{H_{\circ}}\right)^{0.183} * \left(\frac{R}{H_{\circ}}\right)^{0.521} \quad (2.27)$$

As for the semi-circular weirs with the semi-circular edges, the empirical equation is:

$$Q = 0.791 * H_{\circ}^{2.5} * \sqrt{g} * \left(\frac{P}{H_{\circ}}\right)^{0.216} * \left(\frac{R}{H_{\circ}}\right)^{0.505} \quad (2.28)$$

Where, Q is the passing discharge over semi-circular weir, $H_{\circ}$ is water depth over weir's peak, P = height of weir's edge, R = radius of weir's apertures, g is gravitational acceleration.

Based on the above, it is noted that hydraulic characteristics of the flow were studied over different forms of weirs. The study of the hydraulic characteristics of the flow over the circular and semi-circular weirs was discussed with diameters and heights of different peaks and the shape of a different crest.[26]

However, the study of the effect of weir's thickness increment on hydraulic characteristics of semi-circular weir with semi-circular edge has not been studied yet.

In this thesis, the hydraulic characteristics of the flow over the semi-circular weirs with the semi-circular crest will be studied in different thicknesses and different radii and it will be analyzed by using dimensional analysis theory and two statistical methods.

CHAPTER 3

EXPERMENTAL STUDY

3.1 Introduction

This chapter includes a complete description of the experimental program, including clarifying the details of the channel, the equipment used, and the characteristics of the selected weirs. In this study, one experimental program was used.

3.2 Experimental Setup and Equipment

3.2.1 The Experimental Channel (Flume)

Experiments were conducted at the University of Gaziantep in the hydraulic laboratory of civil engineering using a flume rectangular shape with a glass side and a steel bottom with dimensions (length 11.3 m and width 0.8 m and depth 0.9 m). The slope of the flume's bed was zero. The profile view and the top view of the experimental channel is shown in Figure 3.1 - Figure 3.4, and the long of test section was 9 meters. The flow of water is controlled by a valve, while at the end of downstream a sluice gate is installed to control the water depth at the downstream. The experimental channel (flume) is filled by pumping water from the laboratory water tank through the pipes. The discharge is controlled by a valve and an electronic screen is displayed next to it indicating the amount of discharge to be used in the experiment. The discharge was slowly increased and limit to the required experimental value and the discharge remained constant at the same quantity throughout the experiment period.

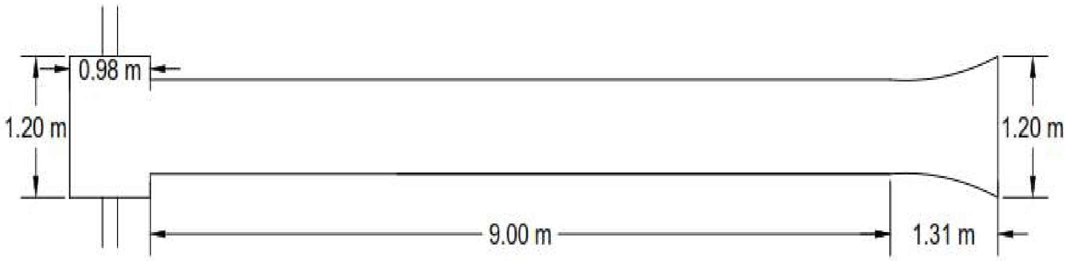

Figure 3.1 Laboratory channel diagram used in experiments

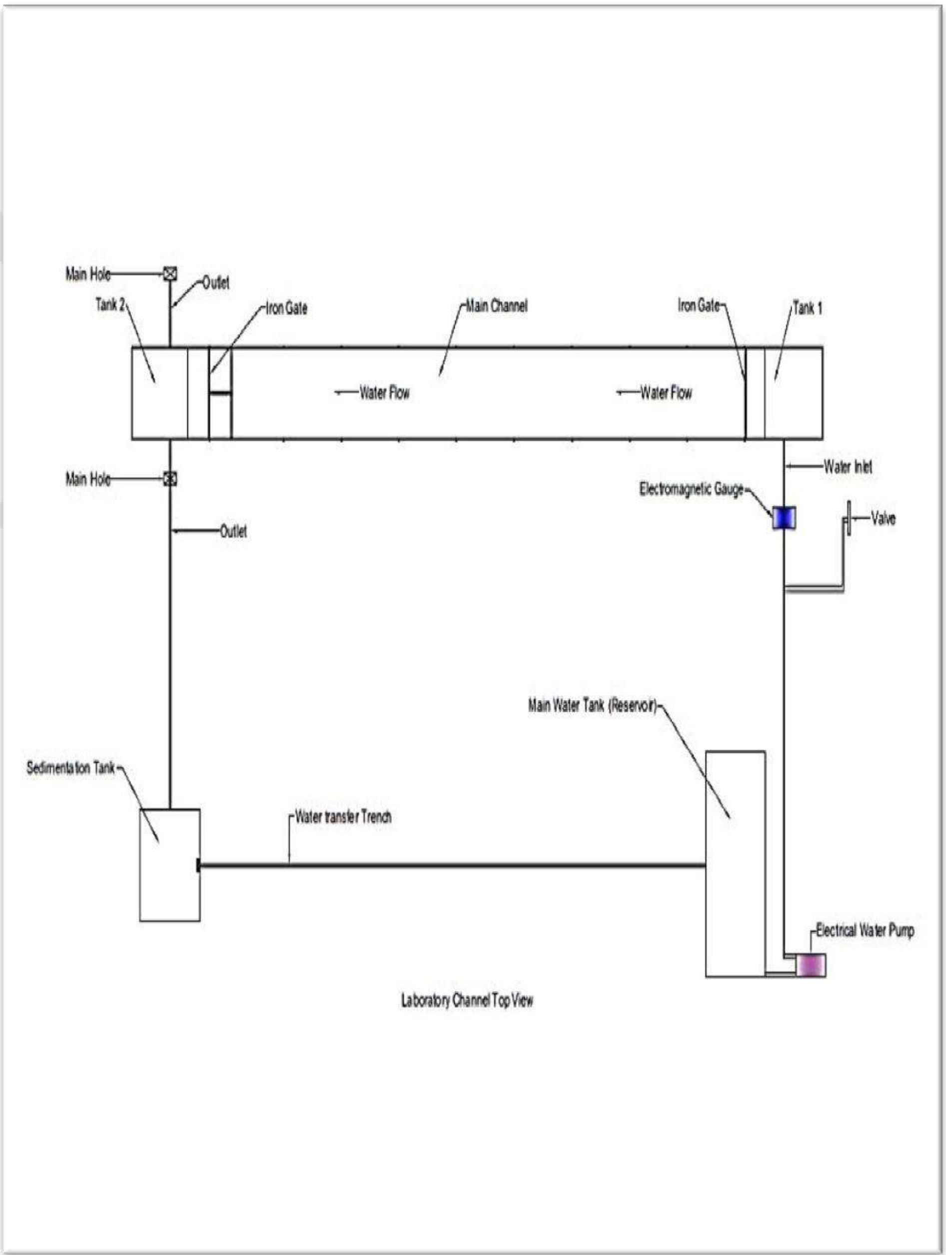

Figure 3.2 Labrotary flume top view

Figure 3.3 Labrotary channel front view

Figure 3.4 Labrotary channel side view

3.2.2 Digital Point Gage

The height of water in the experimental channel (flume) have been taken by using the Digital point gage, Figure 3.5 shows the Digital point gage used in experiments. confirm on the base of the iron moving along the experimental channel (flume). Initially, the device is reset and install to reference subsequent readings. There is a needle at the end of the equipment placed in the surface of water and control the height of the device through the screw located in the canter and the corresponding reading is taken.

Figure 3.5 Digital point gage

3.2.3 Magnetic Flowmeter

A magnetic flow meter has been installed to measure discharge in the piping system infront of the flow path's inlet as shown in Figure 3.6 .

Figure 3.6 Magnetic flowmeter

3.2.4 Water Pump

The hydraulic pumps used in the experiments are one, for the purpose of obtaining different discharges, having a maximum discharge of 250 m^3/hr. They are placed on the right of the experiment channel (flume) and installed on the ground with an iron base near the water supply tank. The pump receives water from this tank through a 4-inch iron pipe and is pumped into the channel by an iron pipe coming out of the pump and connect to the tank at the front of the channel. The outlet discharge from the pump can be controlled by a valve and an electronic scale that can be changed according to the required discharge.as shown in Figure 3.7 below:

Figure 3.7 Pump system

3.3 Models Used in The Study

Semi-circular weirs with semi-circular edge were used in this study after taking the determinants into consideration with the available channel's dimension (height and width), the following values were taken for each the width of weir (B), the height of weir (H) the thickness (T), the radius of weir's aperture (R) and the height of weir's edge (P), Figure 3.8 - 3.16 exhibit the weir's models used in the study and as follows**:**

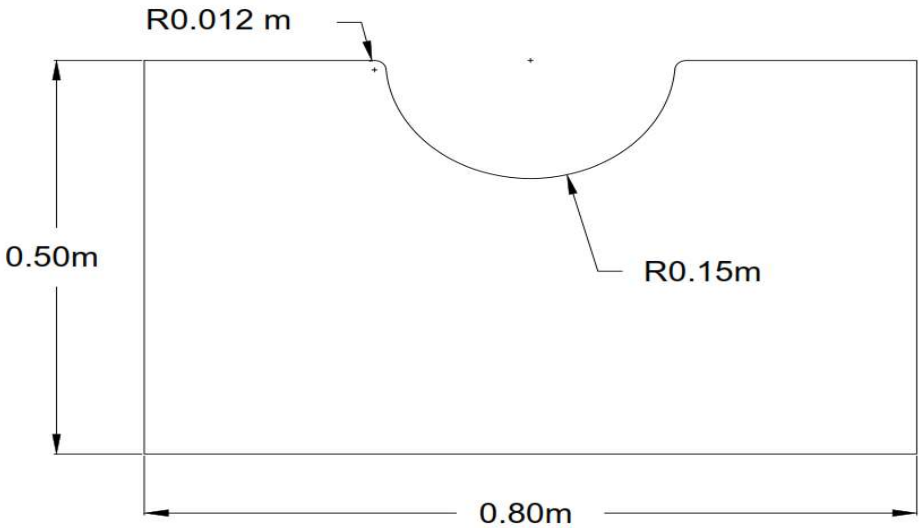

Figure 3.8 Semi-circular weirs with semi-circular edge model with R = 0.15 m

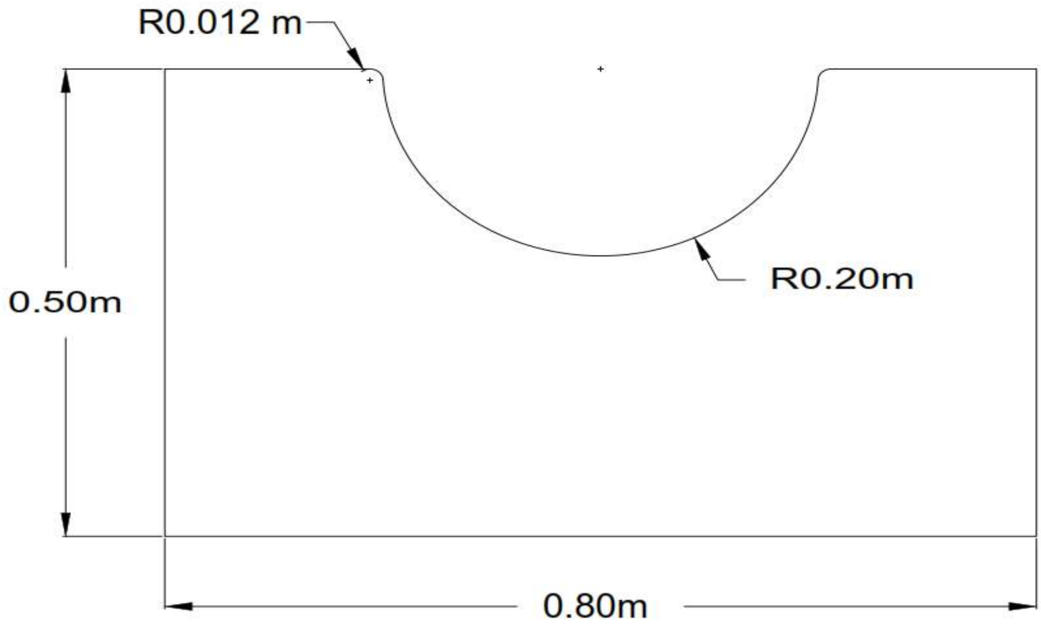

Figure 3.9 Semi-circular weirs with semi-circular edge Model with R = 0.20 m

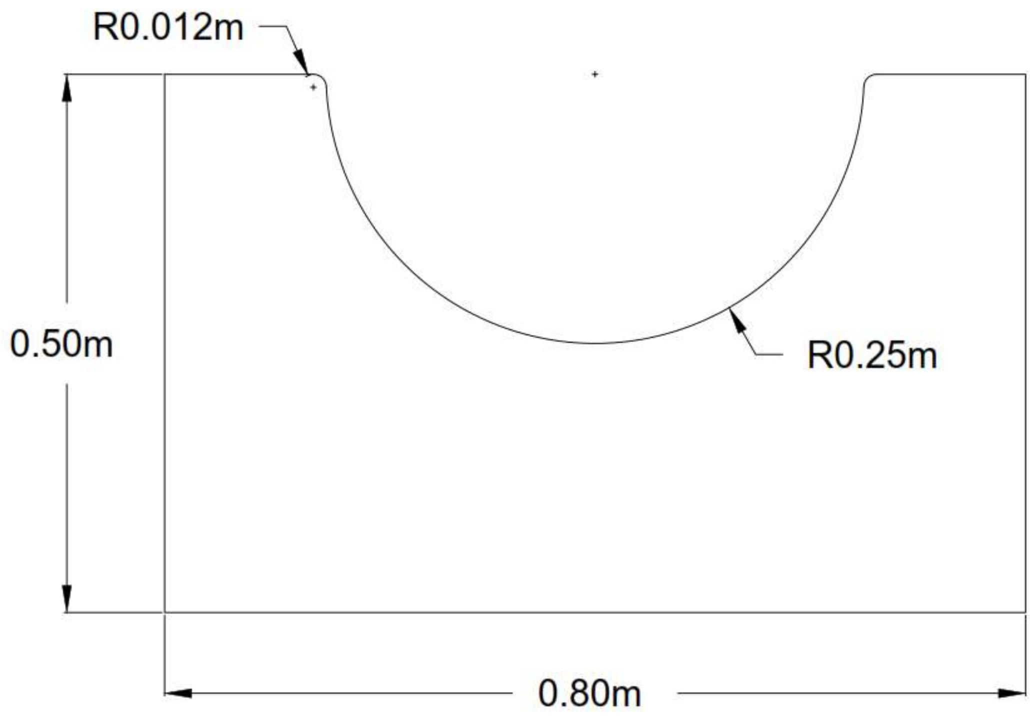

Figure 3.10 Semi-circular weirs with semi-circular edge model with R = 0.25 m

Figure 3.11 Semi-circular weirs with semi-circular edge model with R = 0.15 m

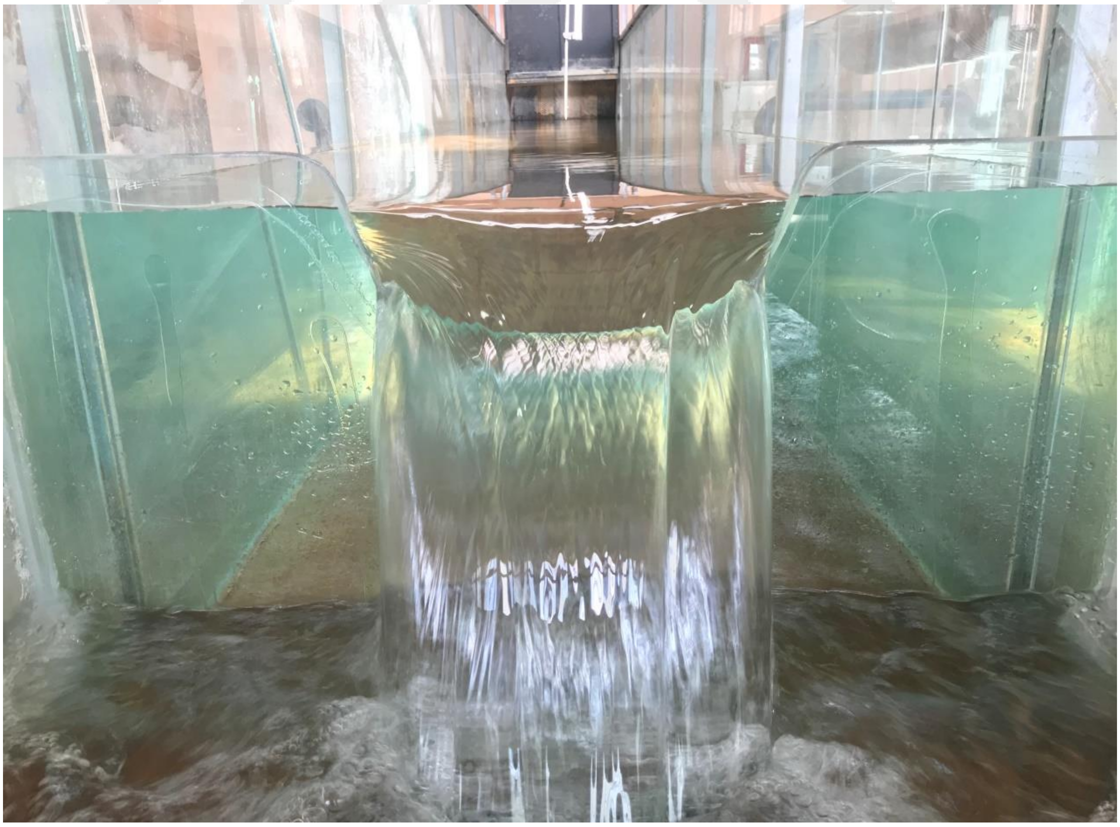

Figure 3.12 Semi-circular weirs with semi-circular edge model with R = 0.15 m during the experiments

Figure 3.13 Semi-circular weirs with semi-circular edge model with R = 0.20 m

Figure 3.14 Semi-circular weirs with semi-circular edge model with R = 0.20 m during the experiments

Figure 3.15 Semi-circular weirs with semi-circular edge model with R = 0.25 m

Figure 3.16 Semi-circular weirs with semi-circular edge model with R = 0.25 m during the experiments

3.4 The Dimensional Analysis

The method of dimensional analysis is one of the mathematical methods used to solve many complex problems, such as fluid mechanics problems. The technique of dimensional analysis assisted laboratory work is the most common method of solving such problems. The method of dimensional analysis is used to create a functional relationship between a number of physical variables (Accredited variables and non-accredited variables) and to reduce to the least number of variables or dimensionless relationships. Since the flow over weir from kinds of complex flow. In this research, this technique was used to find the relationship between variables that affect in the characteristics of the flow over semi-circular weir with semi-circular crest.

There are many factors that influence in the efficiency of the performance and the characteristics of the flow over the semi-circular weirs, such as the engineering dimensions, which represent the thickness of the weir (T), the radius of the weir (R), the height of the crest of the weir (P), the depth of the water over the edge of the weir ($h_{e)}$, the velocity of flow (V), ground acceleration (g) and discharge over the model (Q) in addition to fluid characteristics such as mass density (ρ) and dynamic viscosity (μ), they also affect the characteristics and efficiency of the flow over these sort of weirs.

Therefore, the discharge over the semi-circular weirs is a function of the following variables:

$$Q = f(h_e, P, R, T, v, g, \rho, \mu, \gamma) \tag{3.1}$$

Where, Q is the passing discharge over the semi-circular weir (L^3/T), h_e is the depth of water over weir's edge (L), P is the height of the edge of the weir (L), R = the radius of the weir's opening (L), T = the thickness of the weir (L), V = the velocity of flow (L/T), g = ground acceleration (L/T^2), ρ = mass density for water (M/L^3), μ = dynamic viscosity for water (M/T.L), **γ** = surface tension (M/T^2).

By following the dimensional analysis process using Buckingham's Pie-theory, the following variables were obtained:

$$\pi_1 = \emptyset\,(\pi_2, \pi_3, \pi_4, \pi_5, \pi_6, \pi_7\,) \tag{3.2}$$

By substitute the value of π with its equivalent of variables, the equation becomes:

$$\frac{\boldsymbol{Q}}{\boldsymbol{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}} = \boldsymbol{f}\left(\frac{\boldsymbol{R}}{\boldsymbol{h_e}}, \frac{\boldsymbol{P}}{\boldsymbol{h_e}}, \frac{\boldsymbol{T}}{\boldsymbol{h_e}}, \boldsymbol{Re}, \boldsymbol{Fr}, \boldsymbol{we}\right) \tag{3.3}$$

$$\pi_1 = \frac{Q}{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}} \tag{3.3a}$$

$$\pi_2 = \frac{R}{h_e} \tag{3.3b}$$

$$\pi_3 = \frac{P}{h_e} \tag{3.3c}$$

$$\pi_4 = \frac{T}{h_e} \tag{3.3d}$$

$$\pi_5 = Re \tag{3.3e}$$

$$\pi_6 = Fr \tag{3.3f}$$

$$\pi_7 = We \tag{3.3g}$$

According to Chow (1959), the flow in the channels is turbulent and the viscosity forces are weak relative to the internal forces.[5]

Therefore, the flow in the current study does not depend on the Reynolds number R_e and can be neglected.[13,27,28,29]

Then by rearranging Equation 3.3 will be as follows:

$$\frac{\boldsymbol{Q}}{\boldsymbol{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}} = \boldsymbol{f}\left(\frac{\boldsymbol{R}}{\boldsymbol{h_e}}, \frac{\boldsymbol{P}}{\boldsymbol{h_e}}, \frac{\boldsymbol{T}}{\boldsymbol{h_e}}, \boldsymbol{Fr}, \boldsymbol{we}\right) \tag{3.4}$$

Also, according to Weber (1971), surface tensile forces are low and unaffected, provided that the height of water above the weir's edge h_e is not less than 6 mm, so it can be neglected.[30]

The equation to become as following:

$$\frac{\boldsymbol{Q}}{\boldsymbol{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}} = \boldsymbol{f}\left(\frac{\boldsymbol{R}}{\boldsymbol{h_e}}, \frac{\boldsymbol{P}}{\boldsymbol{h_e}}, \frac{\boldsymbol{T}}{\boldsymbol{h_e}}, \boldsymbol{Fr}\right) \tag{3.5}$$

3.5 Steps of Laboratory Work's Procedure

The semi-circular weirs with semi-circular edge samples were divided into three groups. Each group had a different radius R of 15, 20 and 25 cm. In each of these three groups, the thickness of the weir was changed. Each group consisted of five samples.

In the first group 45 experiments were conducted by changing the thickness of the weir five times (T= 0.4, 0.8, 1.2, 1.6 and 2 cm), and a constant radius of 15 cm and for each model nine different discharges were passed. In the second and third groups, 45 experiments were conducted and the same five thickness were changed with a constant radius of 20 cm for the second group and 25 cm for the third group also nine different discharges were passed for each model.

By using the dimensional-analysis, we find the non-dimensional variables that the discharge of semi-circular weirs with semi-circular crested depend on it.

Laboratory experiments were carried out based on the dimensional analysis process of the factors affecting in the flow characteristics of the semi-circular weir with semi-circular crest. The sequence of work steps for laboratory experiments conducted on these models of weirs used in this study is as follows:

1- The channel is cleaned of all impurities and then the semi-circular weir with a semi-circular crest is formed with a thickness of 0.4 cm and a radius of 15 cm in the last third part of the channel to ensure water stability before crossing the weir as shown in the Figure 3.17 below. Adhesive material is used in the installation process, taking into consideration the water leakage from both sides and from the bottom.

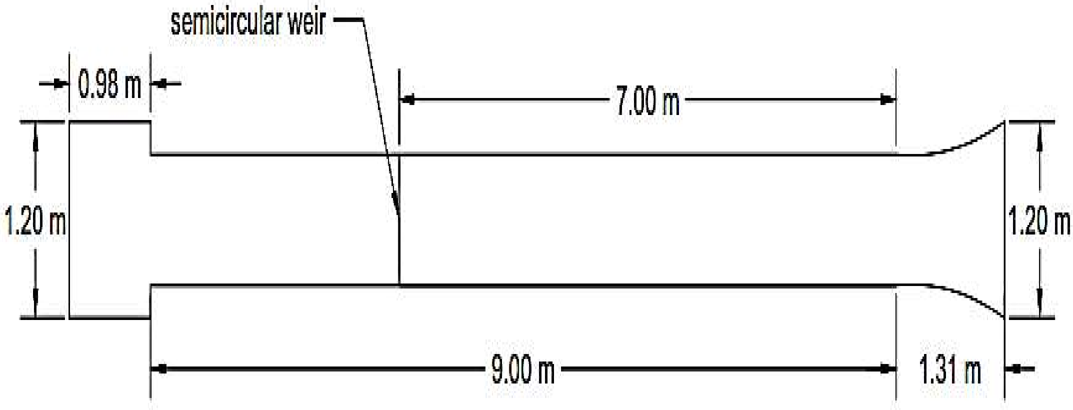

Figure 3.17 The location of the semi-circular weir in the Laboratory flume diagram

2- The pump operated and the valve opened a specific opening for gaining the first discharge and the first rise of water over the weir.
3- Wait until the surface of the water is stabilized. The water height shall be measured over the model of the weir by means of the digital point gage. Where the readings are taken by the digital point gage at a distance of 100 cm before the semi-circular weir with the semi-circular crest and over the weir (h_e), the total of readings is about 10 readings for each discharge, also to ensure the accuracy.
4- The quantity of discharge shall be controlled by change the valve opening and reading the discharge quantity by magnetic flowmeter. Each time a new height of the water surface is recorded above the weir with a semi-circular edge h_e.
5- Repeating the process of change the opening of the valve 9 times to obtain nine different discharges by the pump and take the readings required.
6- After the nine discharges are passed from the pump and the necessary data are taken, the pump is switched off and thus the experiments on the first model are completed.
7- Drain the channel well by emptying the water from it to the storage tank and raise the model and then dry the channel very well and model with a piece of cloth to ensure that the other model paste again at the same place of the channel.
8- Repeat the process from 1 to 7 for the rest models.

Other models should be used with other thicknesses (T = 0.8, 1.2, 1.6 and 2 cm), with the radii (R = 20 and 25 cm), and different heights of the crest of the weir P and the steps are returned from 1 to 8 .

CHAPTER 4

PARAMETRIC STUDY

4.1 General

This chapter includes the analysis and discussion of the results which obtained from experiments on semi-circular weirs with semi-circular crest. The relationship between the variables obtained from the dimension-analysis of the factors influencing on the flow behaviour over these weirs was also plotted with determination of their own the discharge equation Q.

4.2 The Results and Discussion

The tables 4.1 - 4.15 represent the results of laboratory experiments for flow over semi-circular weirs with semi-circular crest, with five thicknesses and three radii.

To state the effect of change the weir's thickness and change the radius of weir and on the discharge equation, the gained results of dimensional analysis (dimensionless parameters) have been plotted and discussed.

The following is an analysis of the results of these tables with an explanation of the relationships that affect the flow characteristics over these weirs.

4.2.1 Effect of Change in The Weir's Thickness (T) on Discharge (Q)

Tables 4.1 - 4.5 represent the results when the radius R = 15 cm and the thickness of the weir (T = 0.4, 0.8, 1.2, 1.6 and 2 cm) respectively, and as follow:

Table 4.1 Laboratory results calculations of flow over semi-circular weirs with semi-circular crest, when T = 0.4 cm, R = 15 cm and P = 35 cm

T (cm)	h_e (mm)	Q (m^3/hr)	$\frac{R}{h_e}$	$\frac{P}{h_e}$	$\frac{T}{h_e}$	$(\frac{Q}{g^{1/2} * {h_e}^{5/2}})$
0.4	13.07	2	11.477	26.779	0.306	9.082
	15.21	3.10	9.862	23.011	0.263	9.636
	19.10	4.10	7.853	18.325	0.209	7.212
	22.55	5	6.652	15.521	0.177	5.807
	24.92	6	6.019	14.045	0.161	5.428
	26.90	7	5.576	13.011	0.149	5.231
	29.35	8.25	5.111	11.925	0.136	4.958
	31.08	9	4.826	11.261	0.129	4.687
	33.15	10	4.525	10.558	0.121	4.433

Table 4.2 Laboratory results calculations of flow over semi-circular weirs with semi-circular crest, when T = 0.8 cm**,** R = 15 cm and P = 35 cm

T (cm)	h_e (mm)	Q (m^3/hr)	$\frac{R}{h_e}$	$\frac{P}{h_e}$	$\frac{T}{h_e}$	$(\frac{Q}{g^{1/2} * {h_e}^{5/2}})$
0.8	21.78	4.10	6.887	16.070	0.367	5.194
	33.50	8.25	4.478	10.448	0.239	3.562
	50.63	16.30	2.963	6.913	0.158	2.506
	70.66	28.10	2.123	4.953	0.113	1.878
	80.76	35	1.857	4.334	0.099	1.675
	87.69	40.20	1.711	3.991	0.091	1.566
	100.23	50	1.497	3.492	0.080	1.394
	111.40	60	1.346	3.142	0.072	1.285
	120.05	70	1.249	2.915	0.067	1.243

Table 4.3 Laboratory results calculations of flow over semi-circular weirs with semi-circular crest, when T = 1.2 cm, R = 15 cm and P = 35 cm

T (cm)	h_e (mm)	Q (m^3/hr)	$\frac{R}{h_e}$	$\frac{P}{h_e}$	$\frac{T}{h_e}$	$(\frac{Q}{g^{1/2} * h_e^{5/2}})$
1.2	25.43	4.10	5.899	13.763	0.472	3.526
	37.15	8.25	4.038	9.421	0.323	2.751
	55.65	16.30	2.695	6.289	0.216	1.979
	74.95	28.10	2.001	4.670	0.160	1.620
	83.87	35	1.788	4.173	0.143	1.524
	91.58	40.20	1.638	3.822	0.131	1.405
	103.04	50	1.456	3.397	0.116	1.301
	114.75	60	1.307	3.050	0.105	1.193
	124.47	70	1.205	2.812	0.096	1.136

Table 4.4 Laboratory results calculations of flow over semi-circular weirs with semi-circular crest, when T = 1.6 cm, R = 15 cm and P = 35 cm

T (cm)	h_e (mm)	Q (m^3/hr)	$\frac{R}{h_e}$	$\frac{P}{h_e}$	$\frac{T}{h_e}$	$(\frac{Q}{g^{1/2} * h_e^{5/2}})$
1.6	24.10	4.10	6.224	14.523	0.664	4.033
	36.10	8.25	4.155	9.695	0.443	2.955
	54.23	16.30	2.766	6.454	0.295	2.111
	73.10	28.10	2.052	4.788	0.219	1.725
	82.21	35	1.825	4.257	0.195	1.602
	89.93	40.20	1.668	3.892	0.178	1.470
	101.78	50	1.474	3.439	0.157	1.342
	112.20	60	1.337	3.119	0.143	1.262
	122.80	70	1.221	2.850	0.130	1.175

Table 4.5 Laboratory results calculations of flow over semi-circular weirs with semi-circular crest, when T = 2 cm, R = 15 cm and P = 35 cm

T (cm)	h_e (mm)	Q (m^3/hr)	$\frac{R}{h_e}$	$\frac{P}{h_e}$	$\frac{T}{h_e}$	$(\frac{Q}{g^{1/2} * h_e{}^{5/2}})$
2	21.95	4.10	6.834	15.945	0.911	5.094
	34.17	8.25	4.390	10.243	0.585	3.390
	52.40	16.30	2.863	6.679	0.382	2.300
	70.29	28.10	2.134	4.979	0.285	1.903
	80.90	35	1.854	4.326	0.247	1.667
	87.70	40.20	1.710	3.991	0.228	1.565
	98.92	50	1.516	3.538	0.202	1.441
	109.66	60	1.368	3.192	0.182	1.336
	120.10	70	1.249	2.914	0.167	1.242

It was noted from Tables 4.1 – 4.5 that the discharge of the weir increases with increasing the thickness from 0.4 cm to 1.2 cm, but at the thickness 1.6 cm it was observed that the discharge started to decrease. Therefore, the thickness of weir was chosen 1.4 cm as a medium case to find the critical thickness at which the discharge changes. In order to determine the radius in which the discharge is changed, and which represents the critical thickness.

Figures 4.1 - 4.5 represent the relationship between the dimensionless parameter $\left(\frac{Q}{g^{\frac{1}{2}} * h_e{}^{\frac{5}{2}}}\right)$ and $(\frac{R}{h_e})$ at the change in the thickness of the weir T for five different thicknesses (T = 0.4, 0.8,1.2, 1.6 and 2 cm) and for a constant radius equals 15 cm and height equals 35 cm.

From these figures it is observed that the discharge increases whenever the thickness of the weir increases with constant both of the height of the edge of the weir and the radius. However, this increasing is small when the thickness changes from 0.4 cm to 0.8 cm and the ratio is 10.33%, while it is greater when the weir's thickness changes from 0.8 cm to 1.2 cm and it's ratio 14.6 %. To clarify this situation as we noticed during experiments when the radius is 15 cm and the thickness of the weir is 0.4 cm, the value of water height over the edge of the weir (h_e) at discharge is 8.25 m^3/hr and

(T = 0.4 cm) equals to 29.4 mm, and at (T = 0.8 cm) the amount of water height over the edge of the weir (h_e) is equals to 33.5 mm and 37.2 mm at T = 1.2 cm. After T = 1.2 cm the (h_e) decreases at 1.6 cm to become 36.1 mm and continues in decreasing at 2 cm to equal 34.2 mm, and so on for other shapes.

It is observed from Figure 4.1 – 4.5 that the relationship between the dimensionless parameter and $(\frac{R}{h_e})$ is a direct relationship. In addition, it is noticed from the below figures that the discharge increases with the increment of the weir's thickness until 1.2 cm, while the discharge value starts to decrease. This means that the value of the critical thickness in which it changes is bounded between thickness 1.2 cm and 1.6 cm and that the value of discharge increased and the ratio 10.33% at the thickness 0.8 cm and the ratio is 14.6% at the thickness 1.2 cm while decreasing with ratio 6.31% at the thickness 1.6 cm, to continue in declining at T = 2 cm and the ratio of 9.97%.

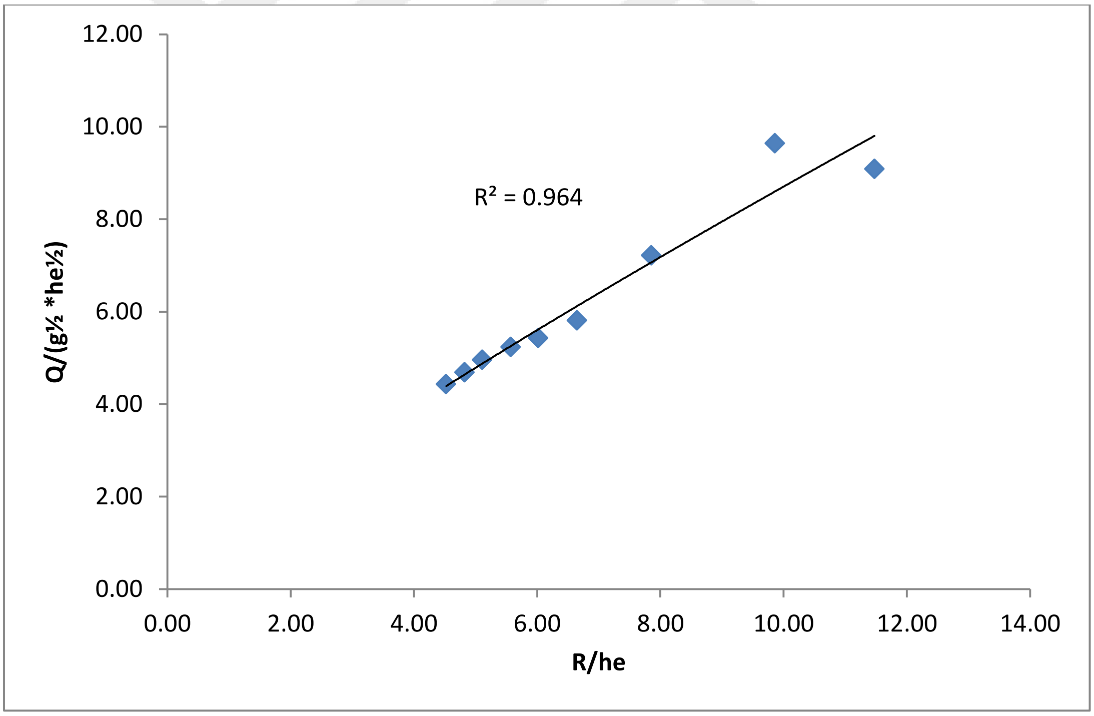

Figure 4.1 Relationship between $\left(\frac{Q}{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}\right)$ and $(\frac{R}{h_e})$ when T= 0.4 cm and R= 15 cm

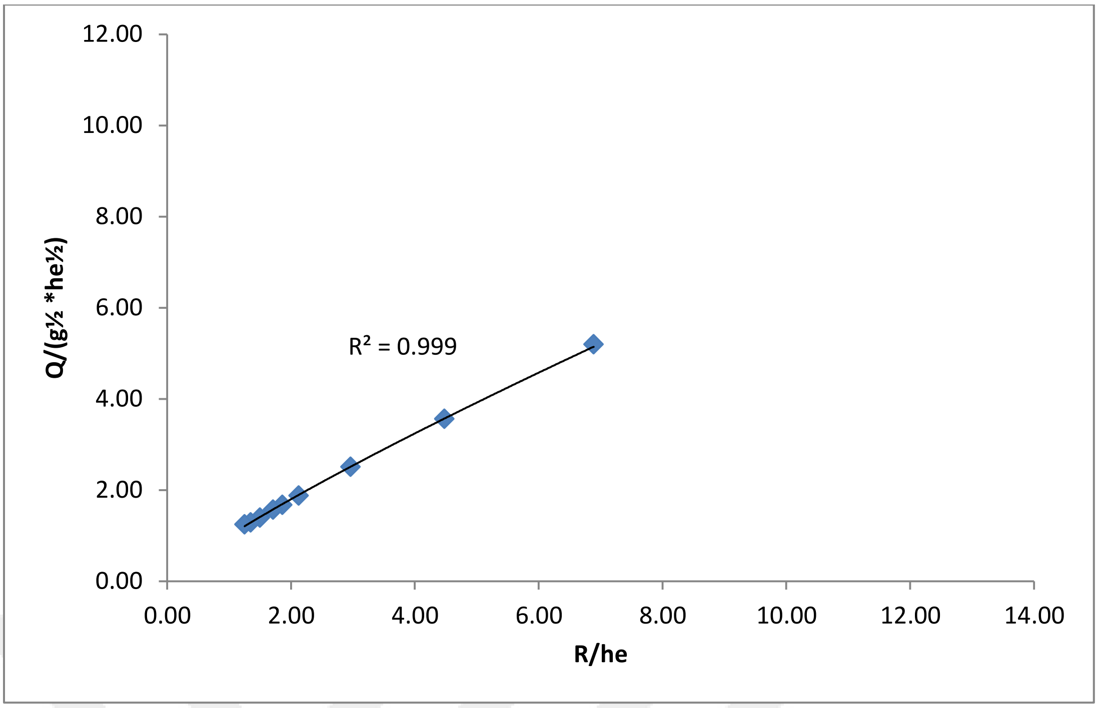

Figure 4.2 Relationship between $\left(\frac{Q}{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}\right)$ and $(\frac{R}{h_e})$ when T= 0.8 cm and R= 15 cm

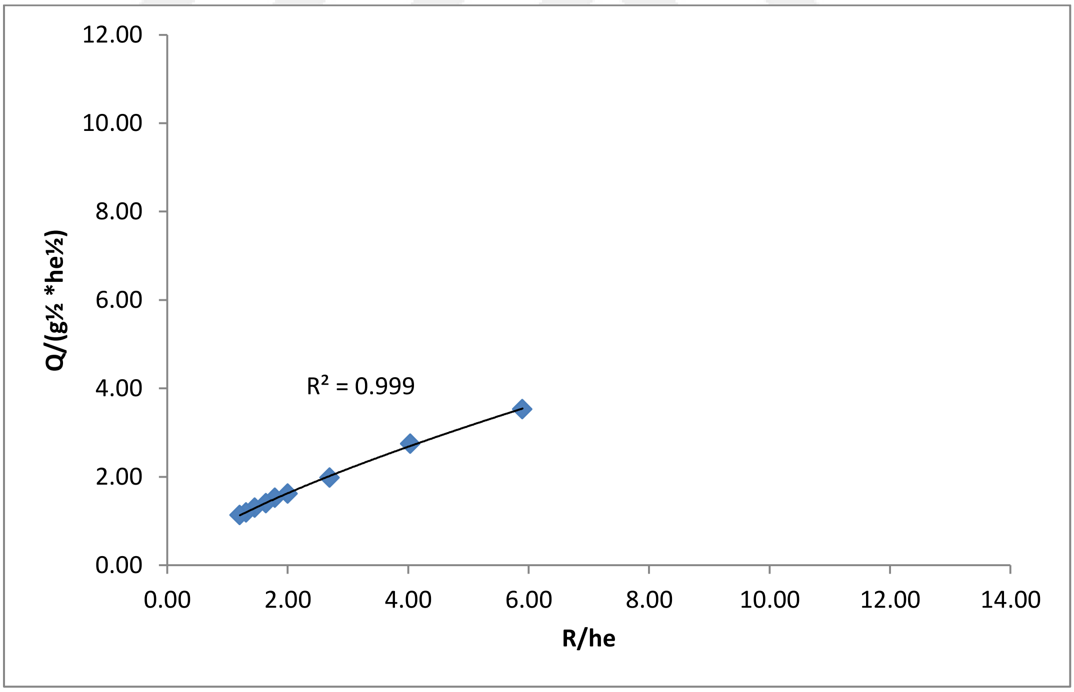

Figure 4.3 Relationship between $\left(\frac{Q}{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}\right)$ and $(\frac{R}{h_e})$ when T= 1.2 cm and R= 15 cm

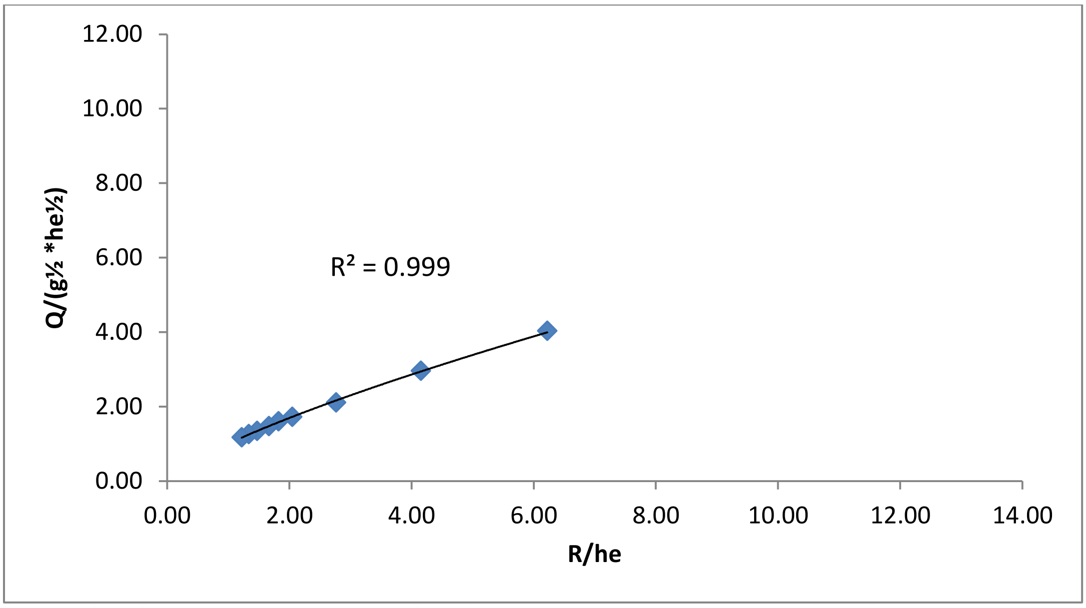

Figure 4.4 Relationship between $\left(\frac{Q}{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}\right)$ and $(\frac{R}{h_e})$ when T= 1.6 cm and R= 15 cm

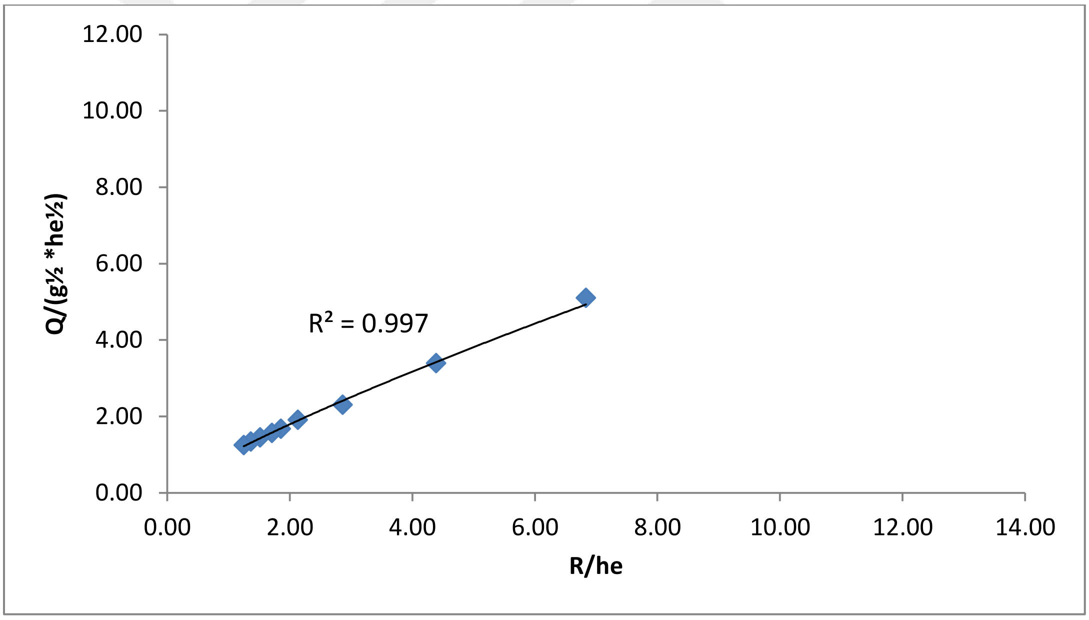

Figure 4.5 Relationship between $\left(\frac{Q}{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}\right)$ and $(\frac{R}{h_e})$ when T= 2 cm and R= 15 cm

Figures 4.6 - 4.10 exhibit the relationship between the dimensionless parameter $\left(\frac{Q}{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}\right)$ and $(\frac{T}{h_e})$ for same radius and thicknesses mentioned up.

It is observed these figures that the relationship between the dimensionless parameter and $(\frac{T}{h_e})$ is a direct relationship. In addition, it is noticed from these figures that the discharge increases with the increment of the weir's thickness till 1.2 cm, while the discharge value starts to decrease. This means that the critical thickness value in which it changes is bounded between the thickness 1.2 cm and 1.6 cm.

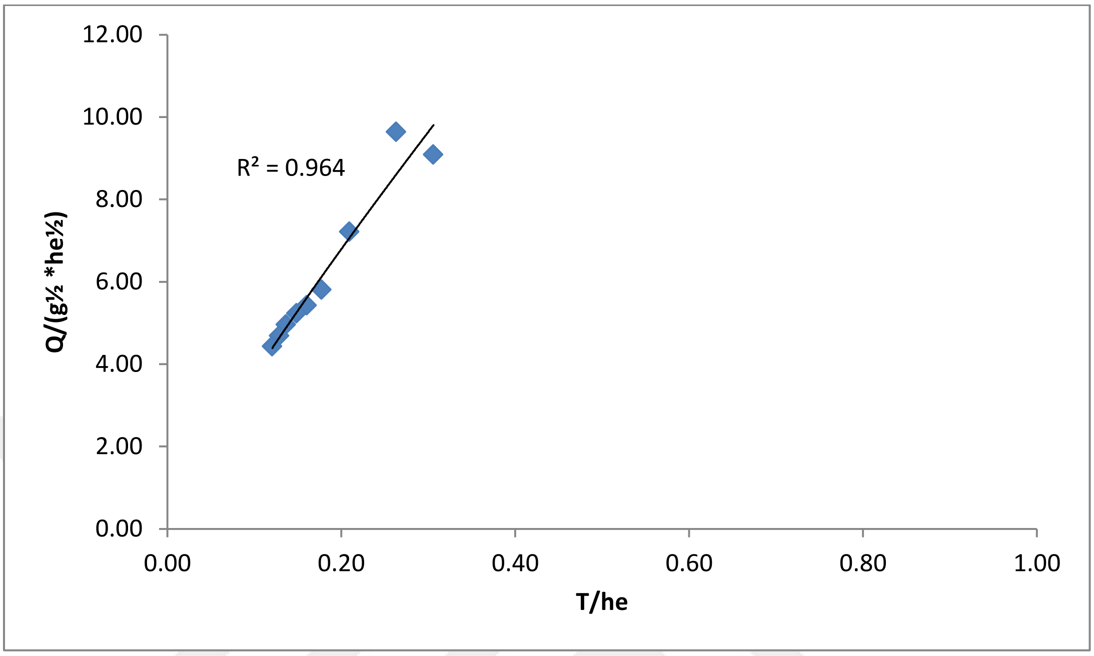

Figure 4.6 Relationship between $\left(\frac{Q}{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}\right)$ and $(\frac{T}{h_e})$ when T= 0.4 cm and R= 15 cm

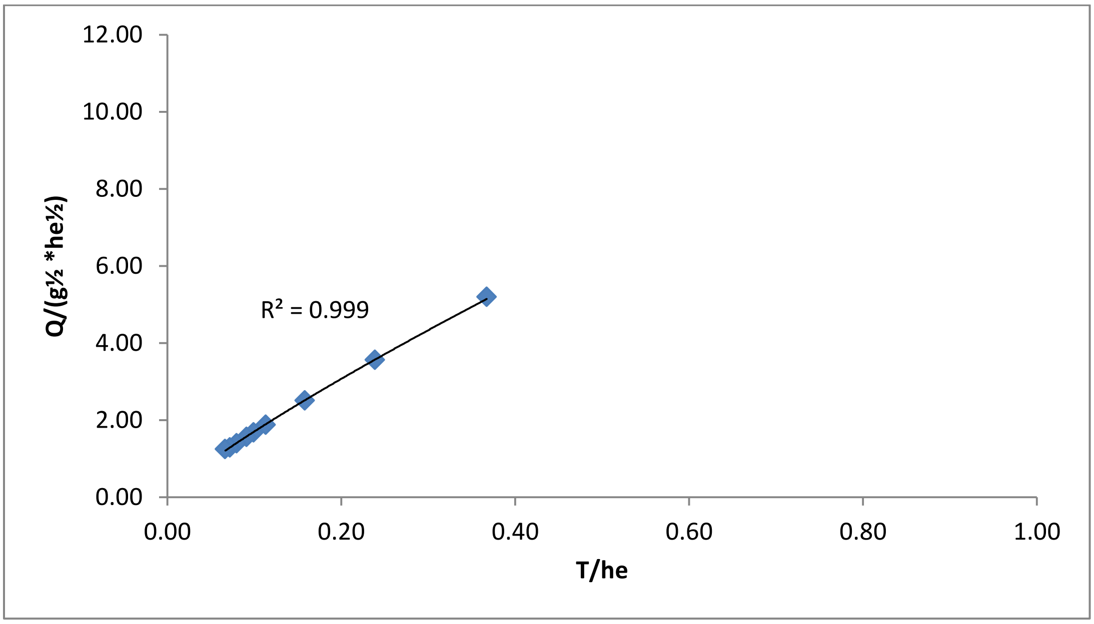

Figure 4.7 Relationship between $\left(\frac{Q}{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}\right)$ and $(\frac{T}{h_e})$ when T= 0.8 cm and R= 0.15 cm

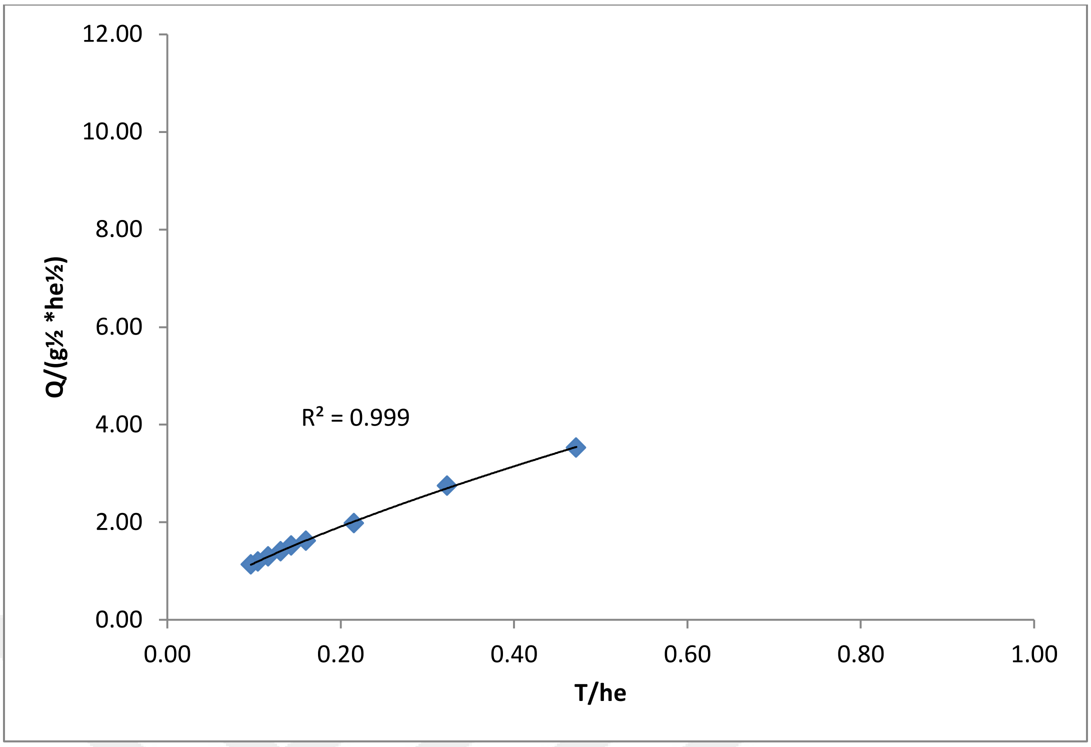

Figure 4.8 Relationship between $\left(\frac{Q}{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}\right)$ and $(\frac{T}{h_e})$ when T= 1.2 cm and R = 15 cm

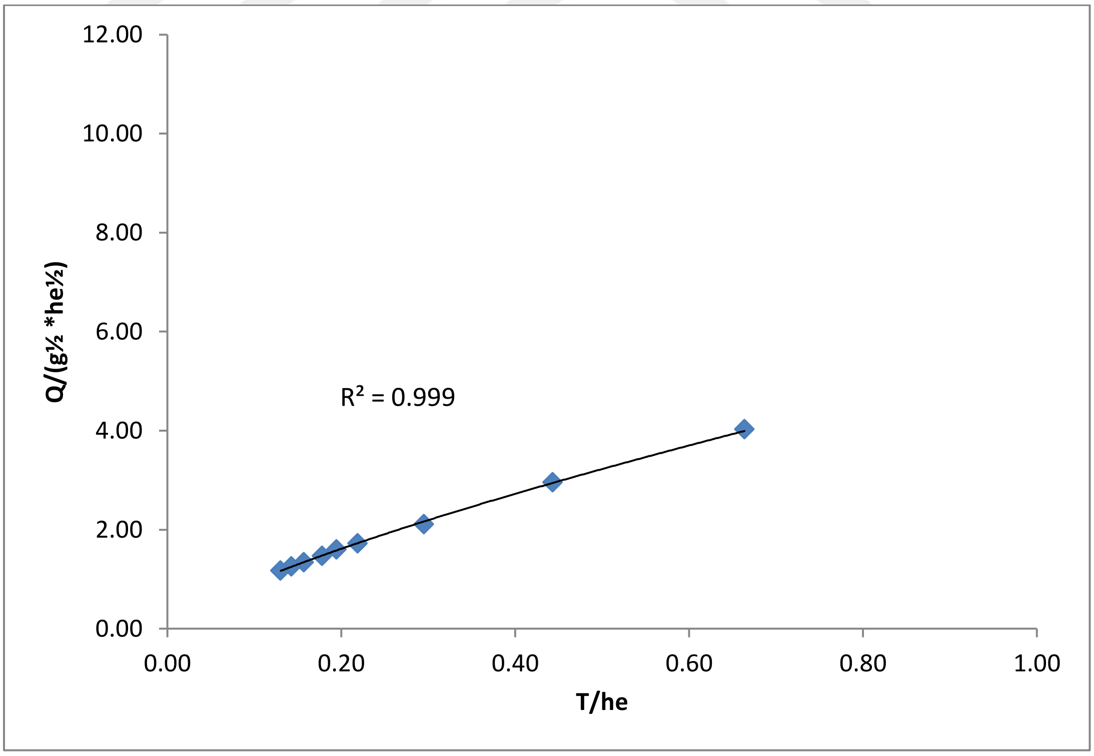

Figure 4.9 Relationship between $\left(\frac{Q}{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}\right)$ and $(\frac{T}{h_e})$ when T= 1.6 cm and R = 15 cm

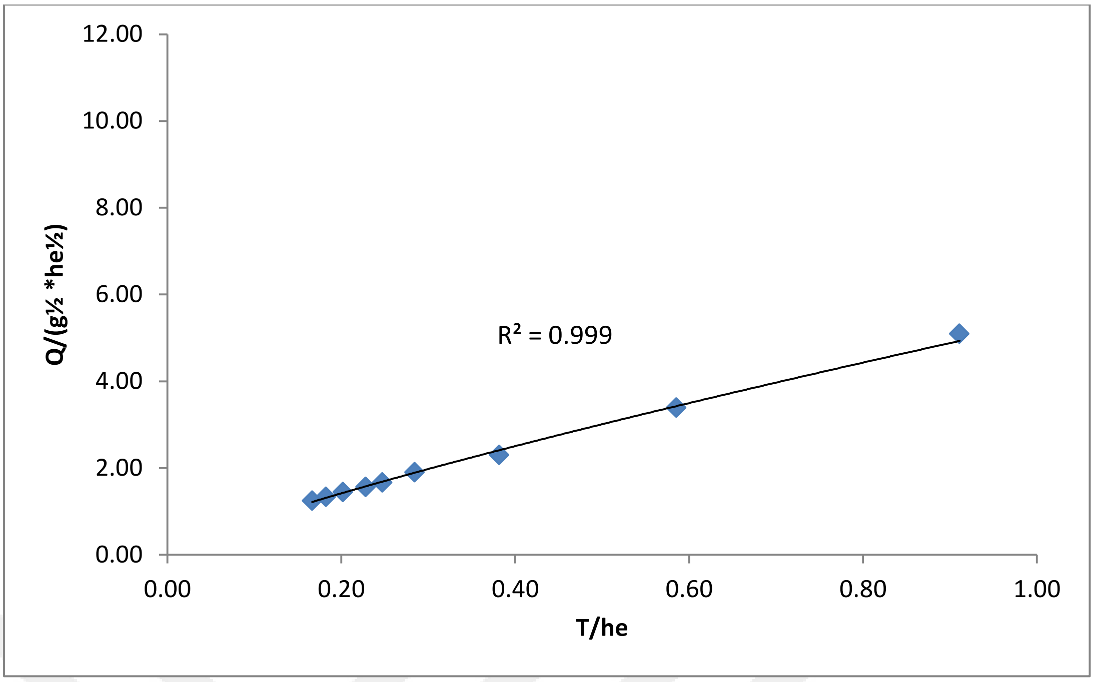

Figure 4.10 Relationship between $\left(\frac{Q}{g^{\frac{1}{2}}*h_e^{\frac{5}{2}}}\right)$ and $(\frac{T}{h_e})$ when T= 2 cm and R= 15 cm

Tables 4.6 - 4.10 represent the results when the radius of the weir's aperture equals to 20 cm and the weir's thickness (T = 0.4, 0.8, 1.2, 1.6 and 2 cm) respectively, and as follow:

Table 4.6 Laboratory results calculations of flow over semi-circular weirs with semi-circular crest, when T = 0.4 cm, R = 20 cm and P = 30 cm

T (cm)	h_e (mm)	Q (m^3/hr)	$\frac{R}{h_e}$	$\frac{P}{h_e}$	$\frac{T}{h_e}$	$(\frac{Q}{g^{1/2}*h_e^{5/2}})$
0.4	10.61	2	18.850	28.275	0.377	15.297
	14.69	3.10	13.615	20.422	0.272	10.512
	18.72	4.10	10.684	16.026	0.214	7.584
	21.22	5	9.425	14.138	0.189	6.760
	23.15	6	8.639	12.959	0.173	6.526
	25.64	7	7.800	11.700	0.156	5.897
	28.20	8.25	7.092	10.638	0.142	5.479
	30.50	9	6.557	9.836	0.131	4.913
	32.62	10	6.131	9.197	0.123	4.615

Table 4.7 Laboratory results calculations of flow over semi-circular weirs with semi-circular crest, when T = 0.8 cm, R = 20 cm and P = 30 cm

T (cm)	h_e (mm)	Q (m^3/hr)	$\frac{R}{h_e}$	$\frac{P}{h_e}$	$\frac{T}{h_e}$	$(\frac{Q}{g^{1/2} * h_e^{5/2}})$
0.8	19.25	4.10	10.390	15.584	0.416	7.072
	30.30	8.25	6.601	9.901	0.264	4.578
	47.17	16.30	4.240	6.360	0.170	2.991
	64.43	28.10	3.104	4.656	0.124	2.365
	74.35	35	2.690	4.035	0.108	2.059
	81.41	40.20	2.457	3.685	0.098	1.885
	91.38	50	2.189	3.283	0.088	1.757
	102.48	60	1.952	2.927	0.078	1.583
	120.00	80	1.667	2.500	0.067	1.422

Table 4.8 Laboratory results calculations of flow over semi-circular weirs with semi-circular crest, when T = 1.2 cm, R = 20 cm and P = 30 cm

T (cm)	h_e (mm)	Q (m^3/hr)	$\frac{R}{h_e}$	$\frac{P}{h_e}$	$\frac{T}{h_e}$	$(\frac{Q}{g^{1/2} * h_e^{5/2}})$
1.2	23.65	4.10	8.457	12.685	0.507	4.227
	34.24	8.25	5.841	8.762	0.350	3.373
	51.90	16.30	3.854	5.780	0.231	2.356
	67.95	28.10	2.943	4.415	0.177	2.071
	77.45	35	2.582	3.873	0.155	1.859
	84.34	40.20	2.371	3.557	0.142	1.726
	94.72	50	2.111	3.167	0.127	1.606
	105.11	60	1.903	2.854	0.114	1.486
	123.49	80	1.620	2.429	0.097	1.324

Table 4.9 Laboratory results calculations of flow over semi-circular weirs with semi-circular crest, when T = 1.6 cm, R = 20 cm and P = 30 cm

T (cm)	h_e (mm)	Q (m^3/hr)	$\frac{R}{h_e}$	$\frac{P}{h_e}$	$\frac{T}{h_e}$	$(\frac{Q}{g^{1/2} * h_e^{5/2}})$
1.6	22.60	4.10	8.850	13.274	0.708	4.736
	33.42	8.25	5.984	8.977	0.479	3.583
	48.77	16.30	4.101	6.151	0.328	2.752
	66.52	28.10	3.007	4.510	0.241	2.184
	76.19	35	2.625	3.938	0.210	1.937
	83.00	40.20	2.410	3.614	0.193	1.796
	93.05	50	2.149	3.224	0.172	1.679
	103.46	60	1.933	2.900	0.155	1.546
	121.30	80	1.649	2.473	0.132	1.385

Table 4.10 Laboratory results calculations of flow over semi-circular weirs with semi-circular crest, when T = 2 cm, R = 20 cm and P = 30 cm

T (cm)	h_e (mm)	Q (m^3/hr)	$\frac{R}{h_e}$	$\frac{P}{h_e}$	$\frac{T}{h_e}$	$(\frac{Q}{g^{1/2} * h_e^{5/2}})$
2	20.14	4.10	9.930	14.896	0.993	6.317
	32.30	8.25	6.192	9.288	0.619	3.902
	46.75	16.30	4.278	6.417	0.428	3.059
	64.15	28.10	3.118	4.677	0.312	2.391
	73.10	35	2.736	4.104	0.274	2.149
	80.01	40.20	2.500	3.750	0.250	1.969
	90.31	50	2.215	3.322	0.221	1.809
	99.45	60	2.011	3.017	0.201	1.706
	118.60	80	1.686	2.530	0.169	1.465

It was noted from Tables 4.6 – 4.10 that the discharge increases with increasing the thickness from 0.4 cm to 1.2 cm, while at the thickness 1.6 cm the discharge began to decrease till T = 2 cm.

Figures 4.11 - 4.15 represent the relationship between the dimensionless parameter $\left(\frac{Q}{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}\right)$ and $(\frac{R}{h_e})$ at the change in the thickness of the weir (T) for five different thicknesses (T = 0.4, 0.8, 1.2, 1.6 and 2 cm), and for a constant radius equals 20 cm and the height equals 30 cm.

It is observed from these figures that the relationship between the dimensionless parameter and $(\frac{R}{h_e})$ is a direct relationship. In addition, it is noticed that the discharge increases with the increment of the weir's thickness until T = 1.2 cm, whearas the discharge value starts to decrease as well. This means that the value of the critical thickness in which it changes is bounded between the thickness 1.2 cm and 1.6 cm and that the value of discharge increased and the ratio 12.17% at the thickness 0.8 cm and the ratio 15.56% at the T = 1.2 cm while decreasing with ratio 6.89% at the thickness 1.6 cm, to continue in declining at T = 2 cm and the ratio is 11.93%.

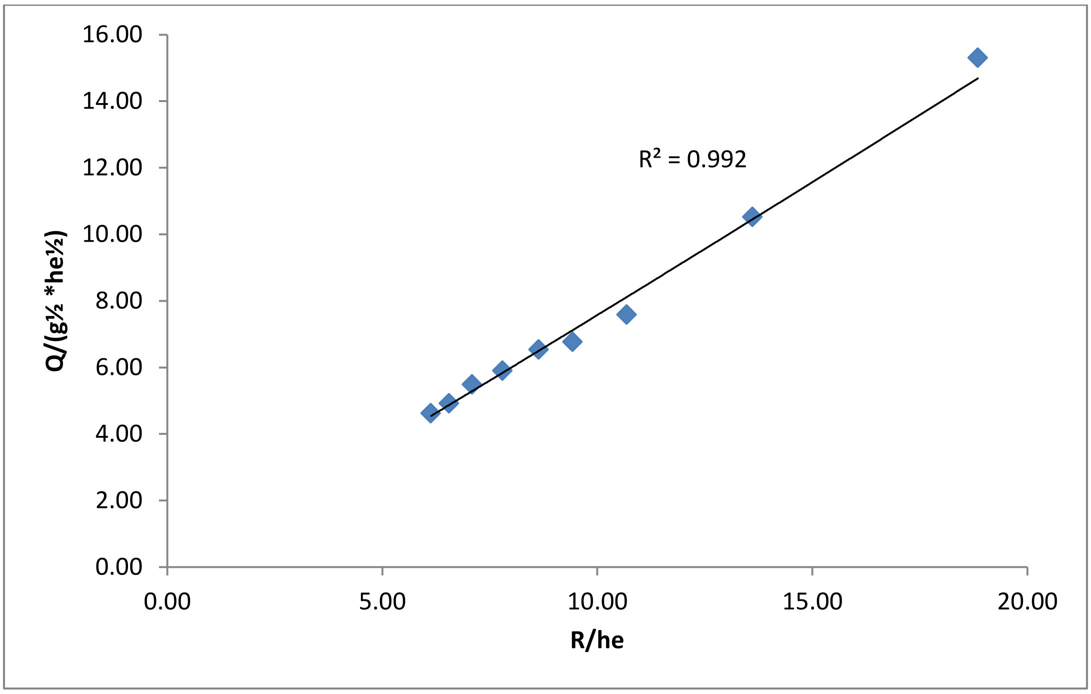

Figure 4.11 Relationship between $\left(\frac{Q}{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}\right)$ and $(\frac{R}{h_e})$ when T= 0.4 cm and R = 20 cm

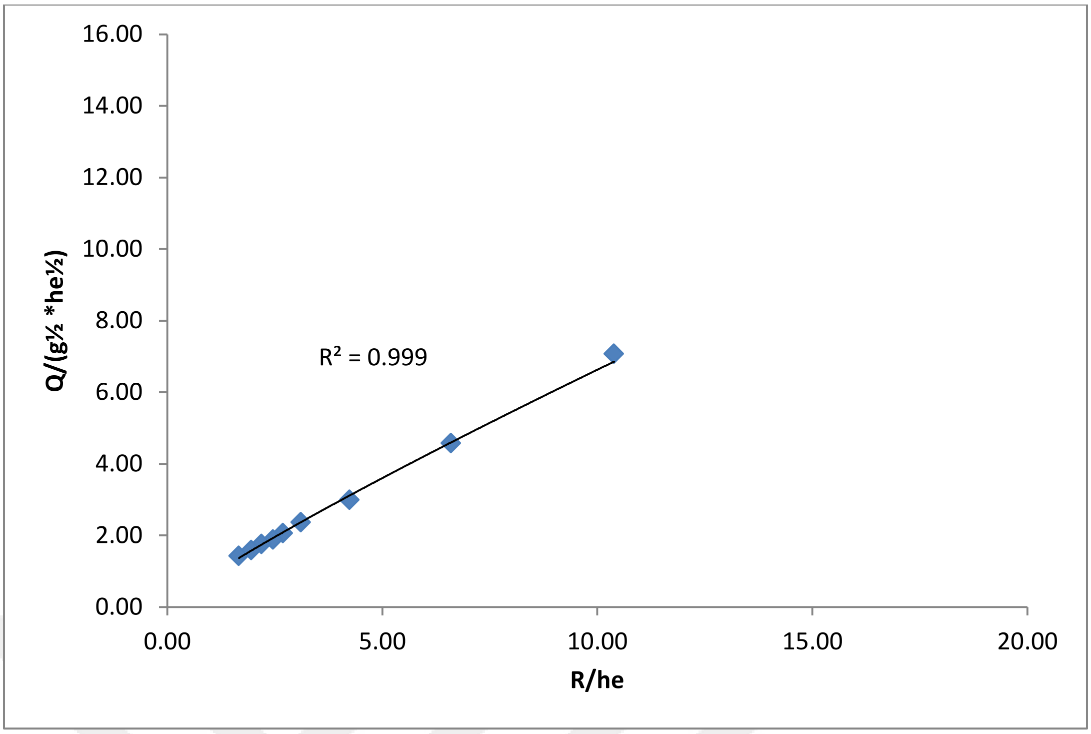

Figure 4.12 Relationship between $\left(\frac{Q}{g^{\frac{1}{2}}*h_e^{\frac{5}{2}}}\right)$ and $(\frac{R}{h_e})$ when T= 0.8 cm and R = 20 cm

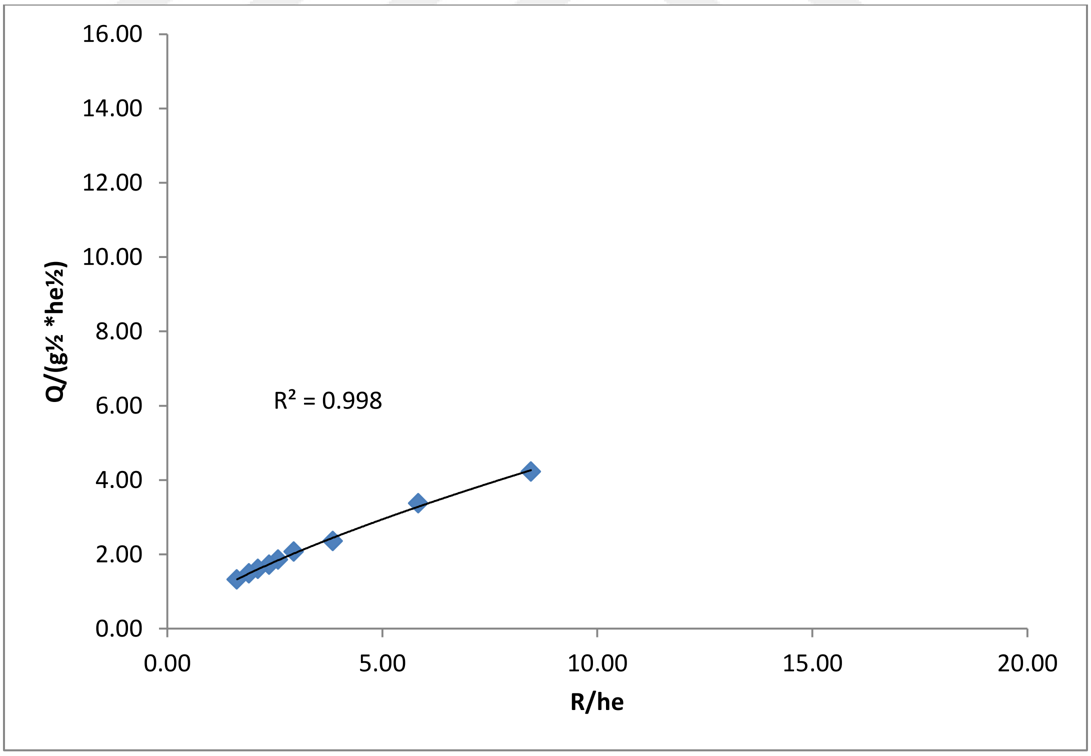

Figure 4.13 Relationship between $\left(\frac{Q}{g^{\frac{1}{2}}*h_e^{\frac{5}{2}}}\right)$ and $(\frac{R}{h_e})$ when T= 1.2 cm and R = 20 cm

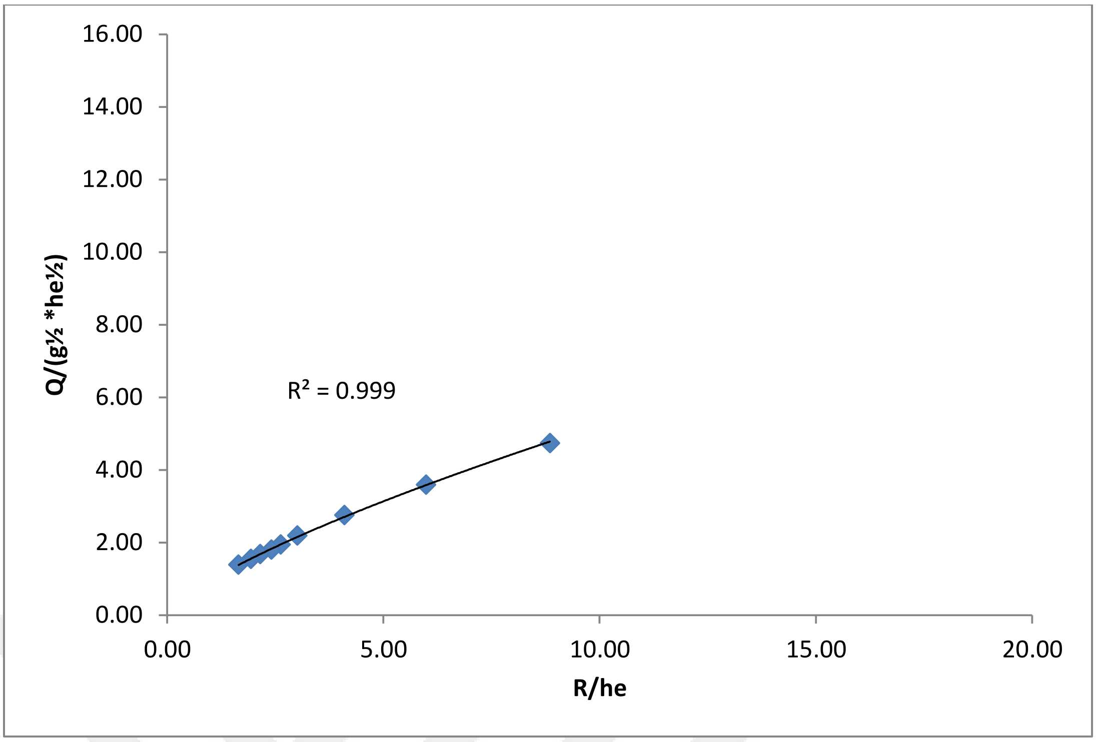

Figure 4.14 Relationship between $\left(\frac{Q}{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}\right)$ and $(\frac{R}{h_e})$ when T= 1.6 cm and R = 20 cm

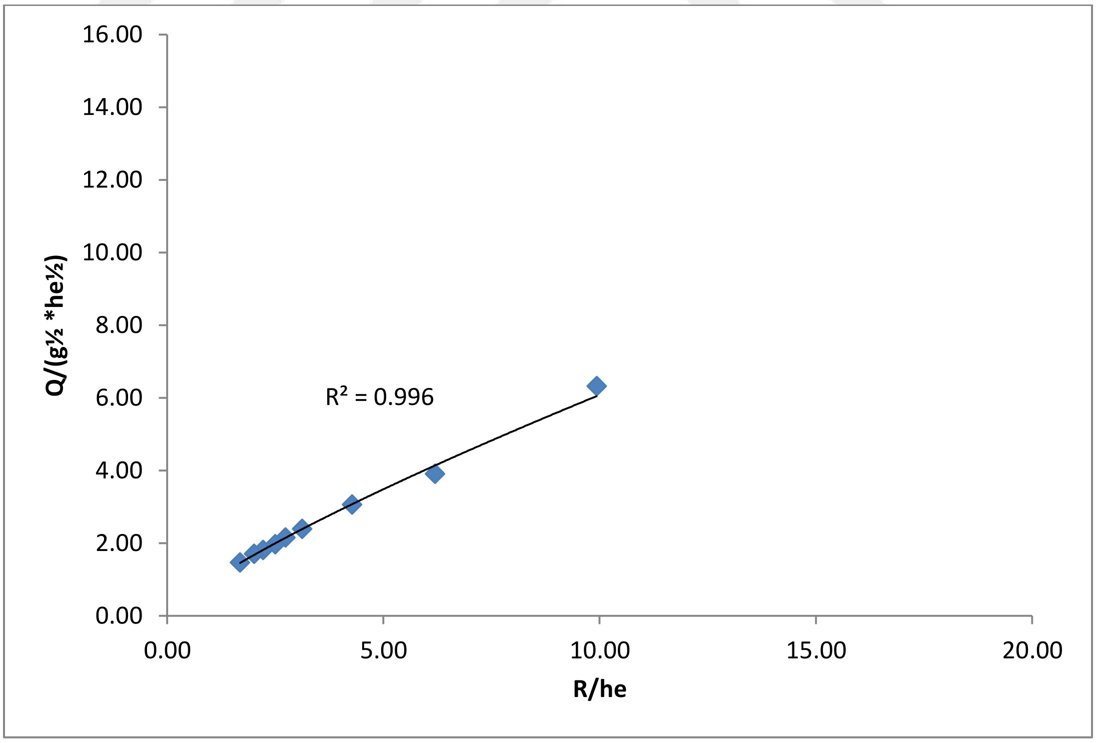

Figure 4.15 Relationship between $\left(\frac{Q}{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}\right)$ and $(\frac{R}{h_e})$ when T= 2 cm and R = 20 cm

Figures 4.16 - 4.20 exhibit the relationship between the dimensionless parameter $\left(\frac{Q}{g^{\frac{1}{2}}*h_e^{\frac{5}{2}}}\right)$ and $(\frac{T}{h_e})$ for same radius and thicknesses mentioned up.

It is observed from the figures that the relationship between the dimensionless parameter and $(\frac{T}{h_e})$ is a direct relationship. Also it is noticed that the discharge increases with the increment of the weir's thickness till 1.2 cm, while the discharge value starts decreasing after T = 1.2 cm. This means that the value of the critical thickness in which it changes is bounded between thickness 1.2 cm and 1.6 cm.

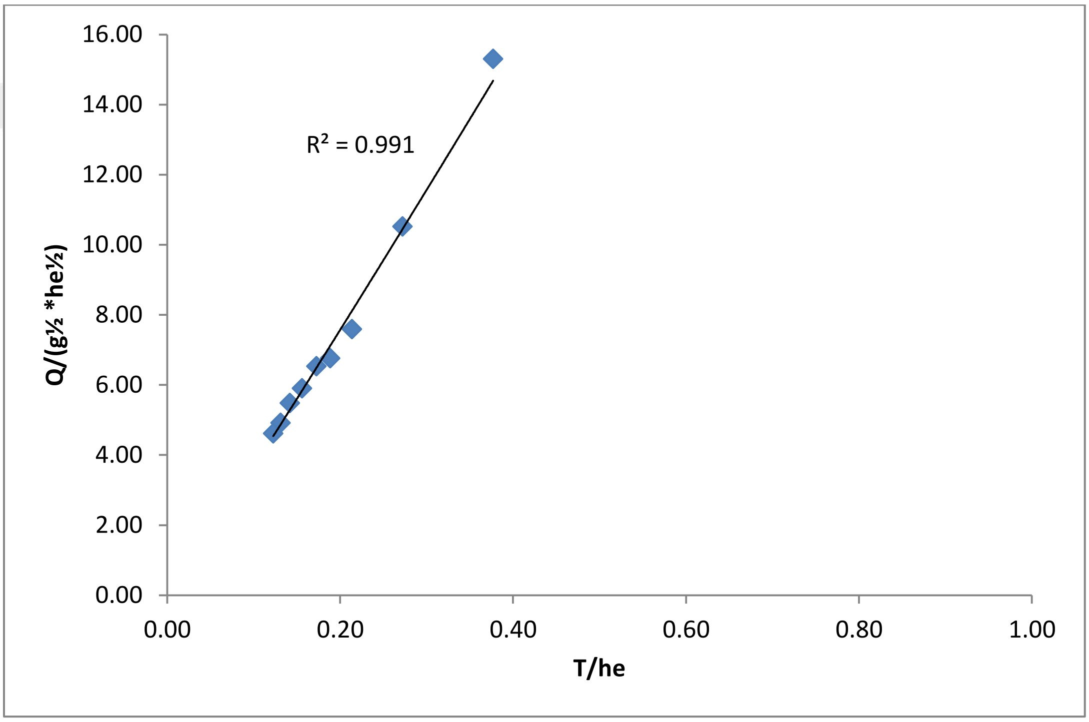

Figure 4.16 Relationship between $\left(\frac{Q}{g^{\frac{1}{2}}*h_e^{\frac{5}{2}}}\right)$ and $(\frac{T}{h_e})$ when T= 0.4 cm and R = 20 cm

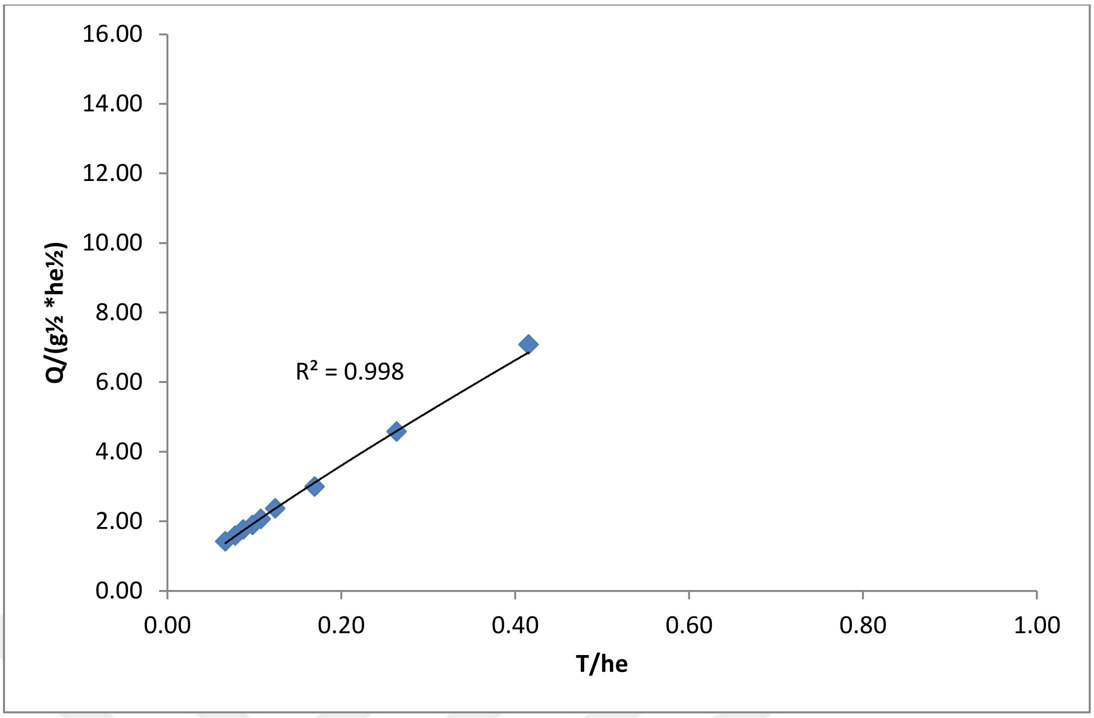

Figure 4.17 Relationship between $\left(\frac{Q}{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}\right)$ and $(\frac{T}{h_e})$ when T= 0.8 cm and R = 20 cm

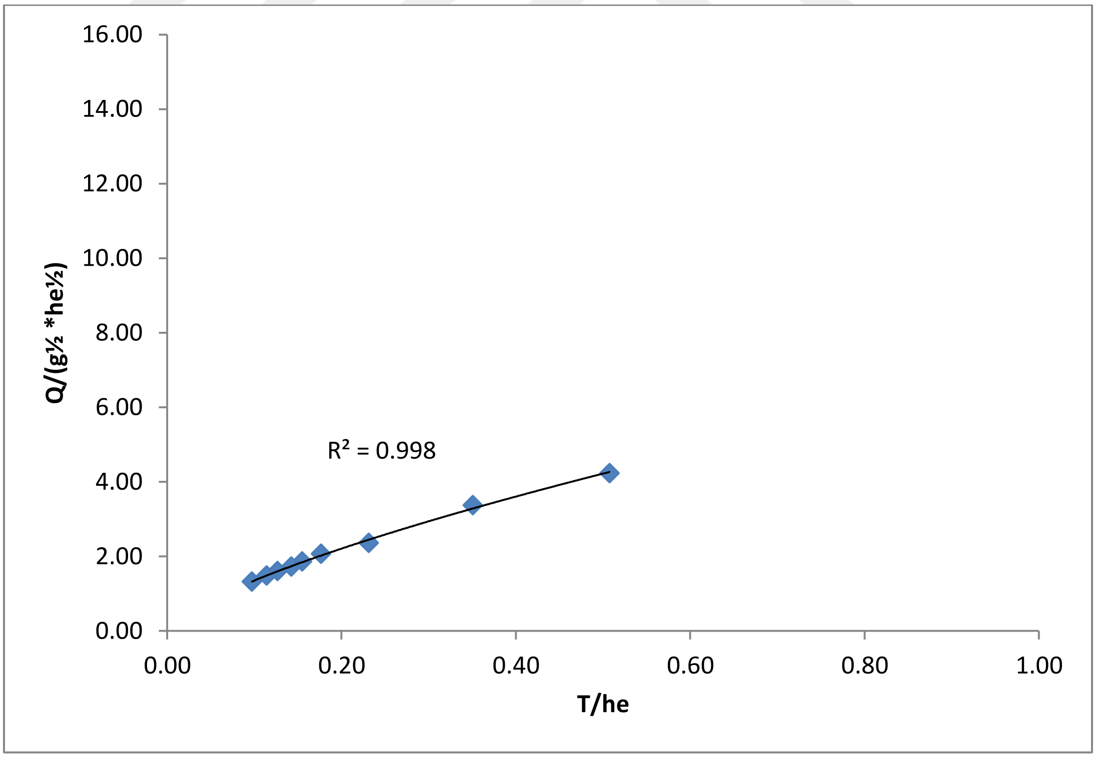

Figure 4.18 Relationship between $\left(\frac{Q}{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}\right)$ and $(\frac{T}{h_e})$ when T= 1.2 cm and R = 20 cm

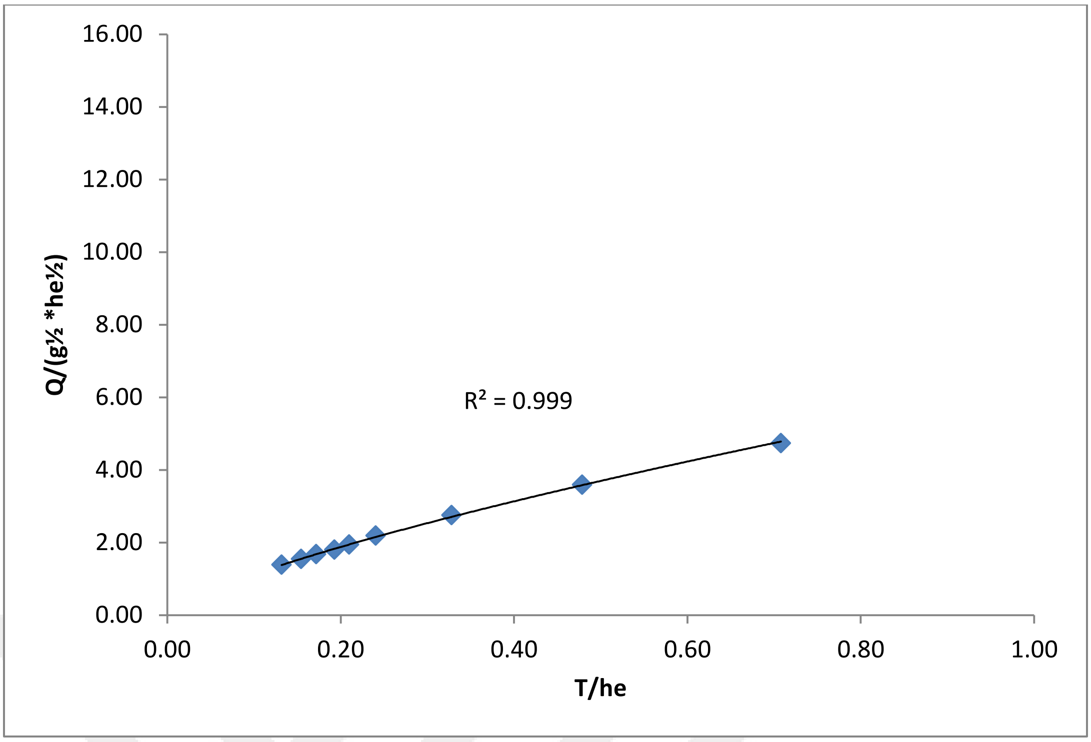

Figure 4.19 Relationship between $\left(\frac{Q}{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}\right)$ and $(\frac{T}{h_e})$ when T= 1.6 cm and R = 20 cm

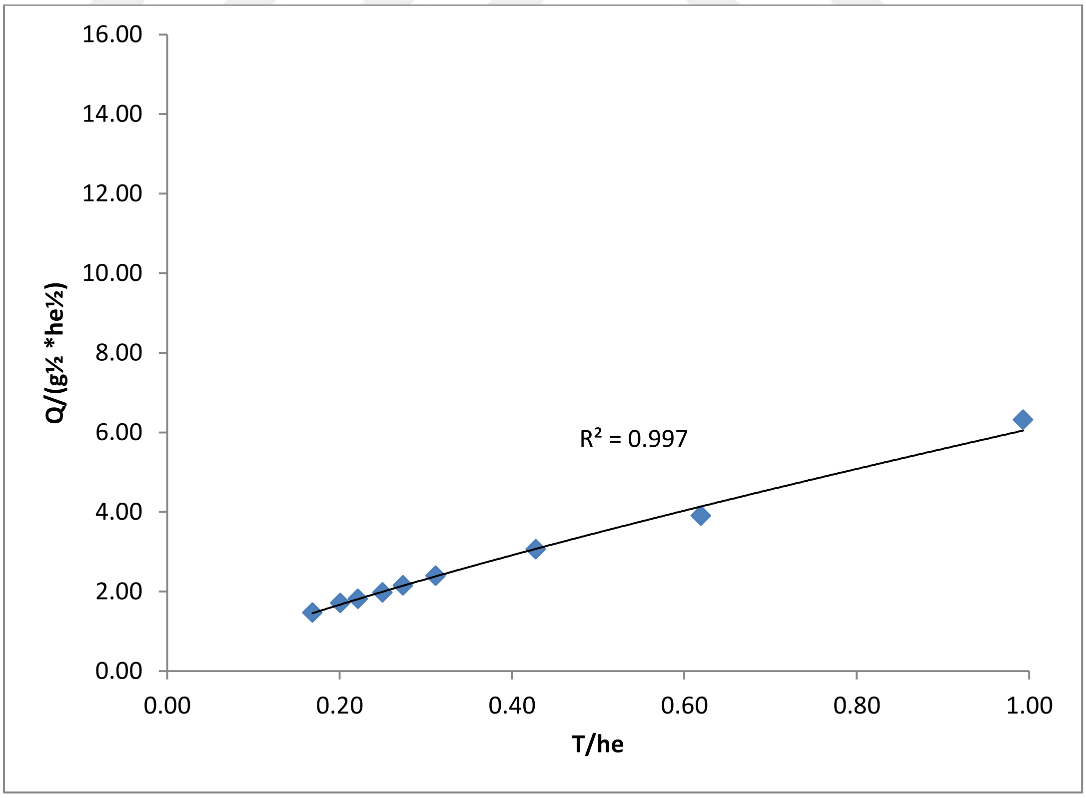

Figure 4.20 Relationship between $\left(\frac{Q}{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}\right)$ and $(\frac{T}{h_e})$ when T= 2 cm and R = 20 cm

Tables 4.11 - 4.15 represent the results when the radius of the weir's aperture = 25 cm and the weir 's thickness (T = 0.4, 0.8, 1.2, 1.6 and 2 cm) respectively, as follow:

Table 4.11 Laboratory results calculations of flow over semi-circular weirs with semi-circular crest, when T = 0.4 cm, R = 25 cm and P = 25 cm

T (cm)	h_e (mm)	Q (m^3/hr)	$\frac{R}{h_e}$	$\frac{P}{h_e}$	$\frac{T}{h_e}$	$(\frac{Q}{g^{1/2}*h_e{}^{5/2}})$
0.4	9.40	2	26.596	26.596	0.426	20.705
	13.51	3.10	18.505	18.505	0.296	12.959
	16.90	4.10	14.793	14.793	0.237	9.793
	19.62	5	12.742	12.742	0.204	8.224
	21.80	6	11.468	11.468	0.183	7.584
	23.77	7	10.517	10.517	0.168	7.127
	26.19	8.25	9.546	9.546	0.153	6.591
	29.05	9	8.606	8.606	0.138	5.549
	31.75	10	7.874	7.874	0.126	4.937

Table 4.12 Laboratory results calculations of flow over semi-circular weirs with semi-circular crest, when (T) = 0.8 cm, (R) = 25 cm and (P) = 25 cm.

T (cm)	h_e (mm)	Q (m^3/hr)	$\frac{R}{h_e}$	$\frac{P}{h_e}$	$\frac{T}{h_e}$	$(\frac{Q}{g^{1/2}*h_e{}^{5/2}})$
0.8	18.00	4.10	13.889	13.889	0.444	8.365
	28.83	8.25	8.672	8.672	0.277	5.184
	44.23	16.30	5.652	5.652	0.181	3.514
	61.85	28.10	4.042	4.042	0.129	2.620
	70.90	35	3.526	3.526	0.113	2.319
	76.83	40.20	3.254	3.254	0.104	2.179
	86.51	50	2.890	2.890	0.092	2.014
	95.17	60	2.627	2.627	0.084	1.904
	111.59	80	2.240	2.240	0.072	1.706

Table 4.13 Laboratory results calculations of flow over semi-circular weirs with semi-circular crest, when T = 1.2 cm, R = 25 cm and P = 25 cm

T (cm)	h_e (mm)	Q (m^3/hr)	$\frac{R}{h_e}$	$\frac{P}{h_e}$	$\frac{T}{h_e}$	$(\frac{Q}{g^{1/2} * h_e{}^{5/2}})$
1.2	21.60	4.10	11.574	11.574	0.556	5.303
	33.11	8.25	7.551	7.551	0.362	3.668
	49.19	16.30	5.082	5.082	0.244	2.694
	65.60	28.10	3.811	3.811	0.183	2.261
	73.92	35	3.382	3.382	0.162	2.089
	79.17	40.20	3.158	3.158	0.152	2.022
	89.16	50	2.804	2.804	0.135	1.868
	98.00	60	2.551	2.551	0.122	1.770
	114.80	80	2.178	2.178	0.105	1.589

Table 4.14 Laboratory results calculations of flow over semi-circular weirs with semi-circular crest, when T = 1.6 cm, R = 25 cm and P = 25 cm

T (cm)	h_e (mm)	Q (m^3/hr)	$\frac{R}{h_e}$	$\frac{P}{h_e}$	$\frac{T}{h_e}$	$(\frac{Q}{g^{1/2} * h_e{}^{5/2}})$
1.6	19.85	4.10	12.594	12.594	0.806	6.550
	31.35	8.25	7.974	7.974	0.510	4.205
	47.00	16.30	5.319	5.319	0.340	3.019
	63.87	28.10	3.914	3.914	0.251	2.417
	71.67	35	3.488	3.488	0.223	2.257
	77.19	40.20	3.239	3.239	0.207	2.154
	87.34	50	2.862	2.862	0.183	1.967
	96.09	60	2.602	2.602	0.167	1.859
	112.98	80	2.213	2.213	0.142	1.654

Table 4.15 Laboratory results calculations of flow over semi-circular weirs with semi-circular crest, when T = 2 cm, R = 25 cm and P = 25 cm

T (cm)	h_e (mm)	Q (m^3/hr)	$\frac{R}{h_e}$	$\frac{P}{h_e}$	$\frac{T}{h_e}$	$(\frac{Q}{g^{1/2} * h_e^{5/2}})$
2	17.38	4.10	14.384	14.384	1.151	9.131
	28.35	8.25	8.818	8.818	0.705	5.407
	44.02	16.30	5.679	5.679	0.454	3.556
	60.90	28.10	4.105	4.105	0.328	2.723
	69.11	35	3.617	3.617	0.289	2.472
	74.49	40.20	3.356	3.356	0.268	2.354
	84.85	50	2.946	2.946	0.236	2.114
	92.33	60	2.708	2.708	0.217	2.054
	109.16	80	2.290	2.290	0.183	1.802

It was noted from Tables 4.11 – 4.15 that the discharge increases with increasing the thickness from 0.4 cm to 1.2 cm, while at the thickness 1.6 cm the discharge began to decrease until the thickness 2 cm.

Figures 4.21 - 4.25 represent the relationship between the dimensionless parameter $\left(\frac{Q}{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}\right)$ and $(\frac{R}{h_e})$ at the change in the thickness of the weir for five different thicknesses (T = 0.4, 0.8, 1.2, 1.6 and 2 cm) and for a constant radius of 25 cm and the height of 25 cm.

It is observed from Figures 4.21 – 4.25 that the relationship between the dimensionless parameter and $(\frac{R}{h_e})$ is a direct relationship. In addition, it is noticed from these figures that the discharge increases with the increment of the weir's thickness till 1.2 cm, while the discharge value starts to decrease. This means that the value of the critical thickness is bounded between 1.2 cm and 1.6 cm, and that the value of discharge accordingly increased and the ratio is 12.61% at T = 0.8 cm and the ratio is 15.70% at T = 1.2 cm while decreasing with ratio 9.57% at T = 1.6 cm, and results declining the thickness as 2 cm a ratio of 16.02%.

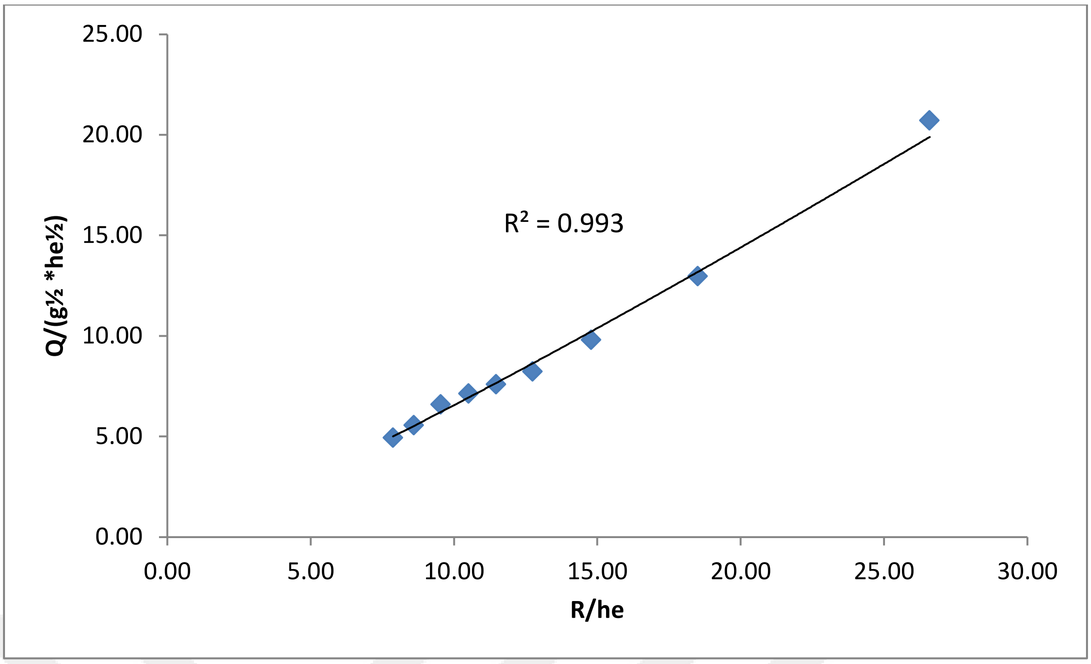

Figure 4.21 Relationship between $\left(\frac{Q}{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}\right)$ and $(\frac{R}{h_e})$ when T= 0.4 cm and R = 25 cm

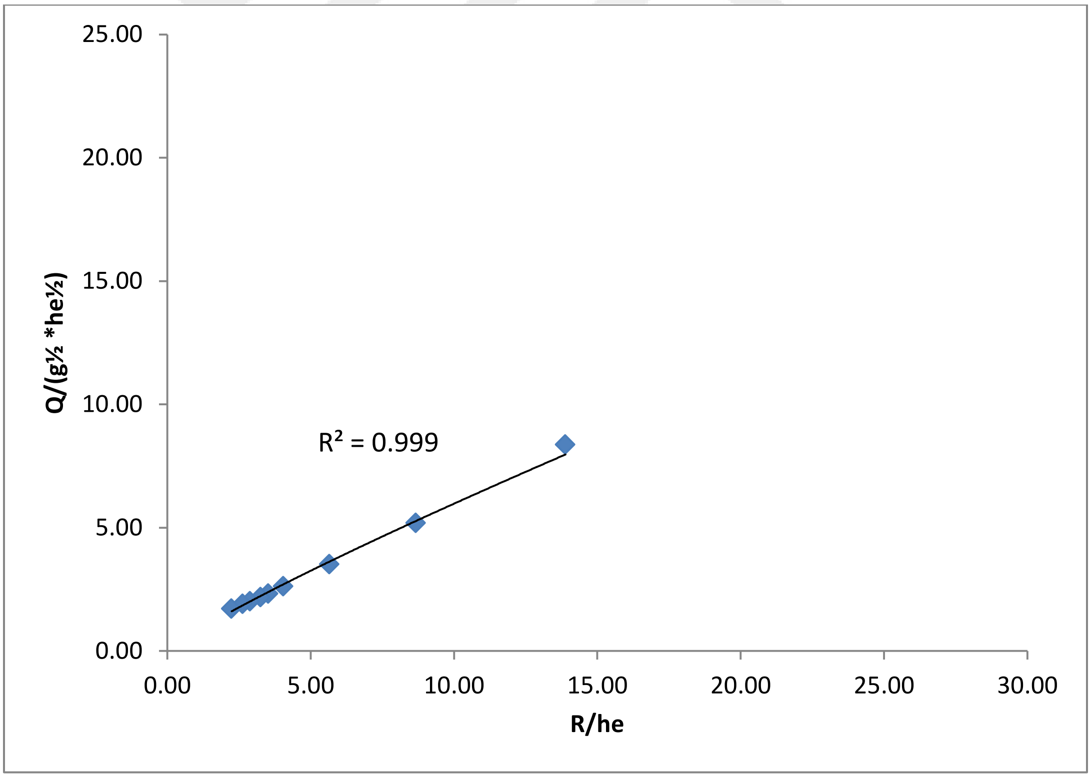

Figure 4.22 Relationship between $\left(\frac{Q}{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}\right)$ and $(\frac{R}{h_e})$ when T= 0.8 m and R = 25 cm

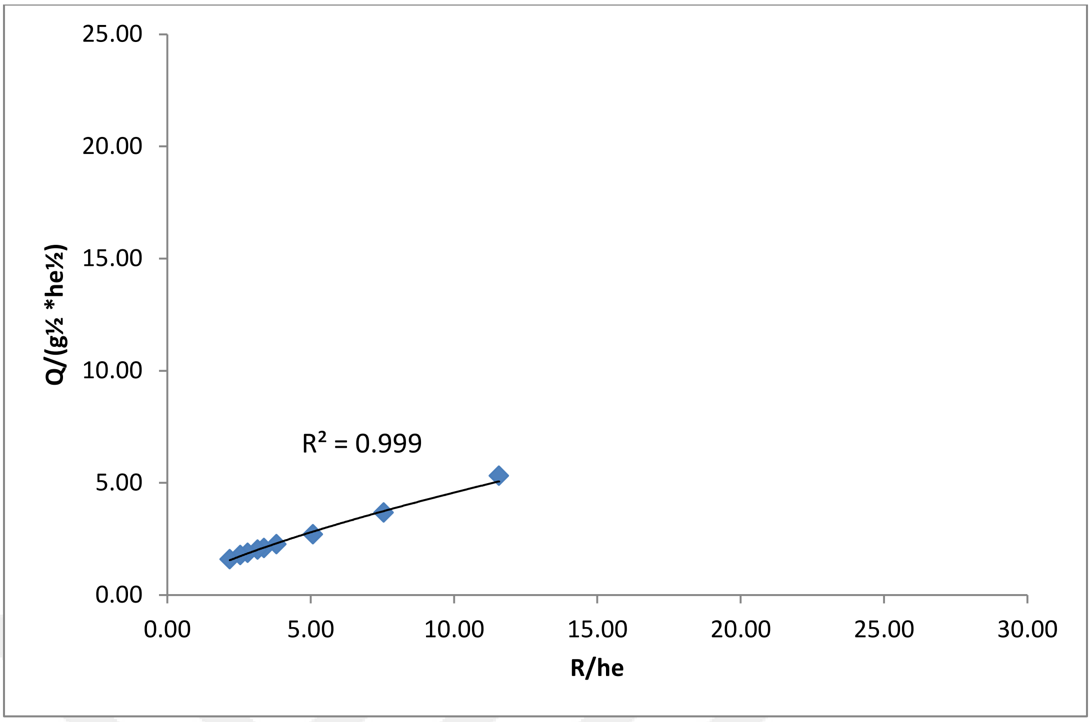

Figure 4.23 Relationship between $\left(\frac{Q}{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}\right)$ and $(\frac{R}{h_e})$ when T= 1.2 cm and R = 25 cm

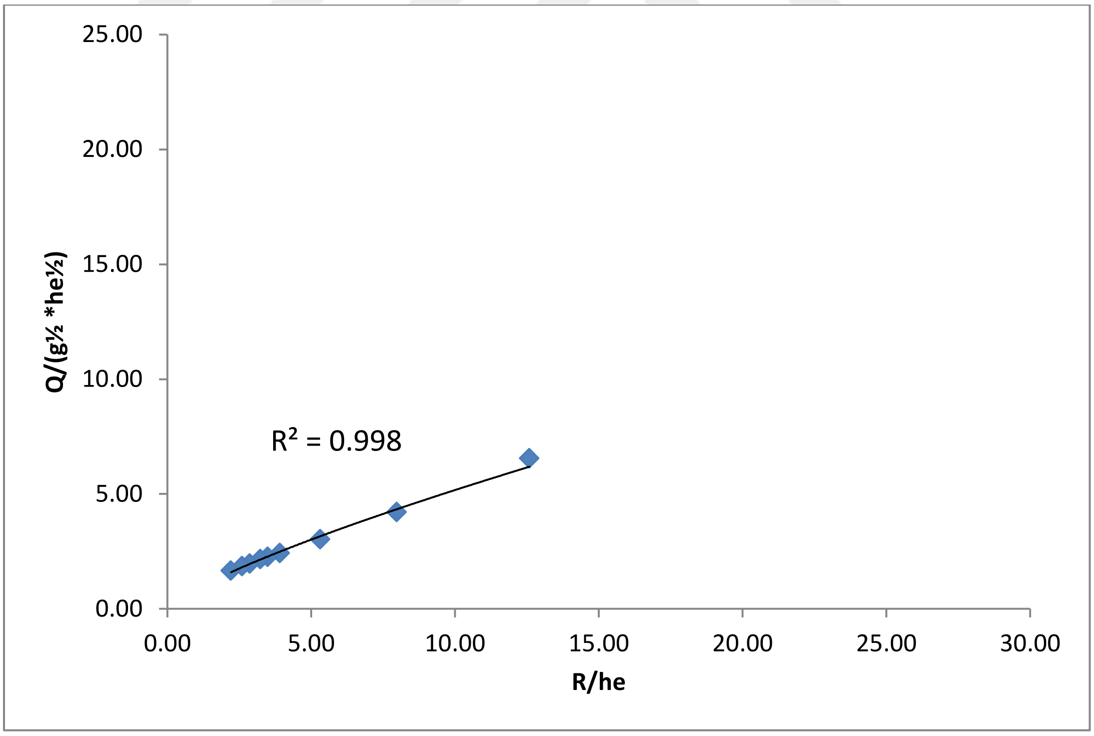

Figure 4.24 Relationship between $\left(\frac{Q}{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}\right)$ and $(\frac{R}{h_e})$ when T= 1.6 cm and R = 25 cm

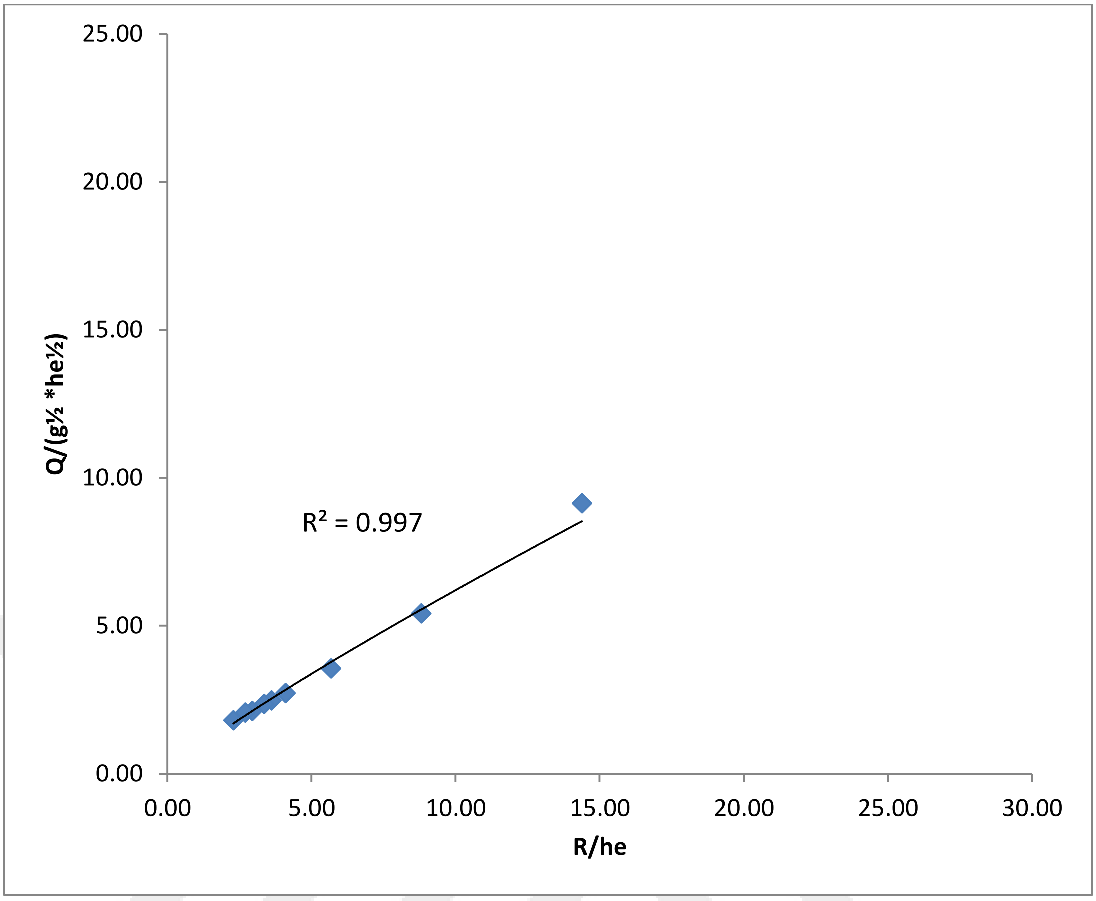

Figure 4.25 Relationship between $\left(\frac{Q}{g^{\frac{1}{2}}*h_e^{\frac{5}{2}}}\right)$ and $(\frac{R}{h_e})$ when T= 2 cm and R = 25 cm

Figures from 4.26 - 4.30 exhibit the relationship between the dimensionless parameter $\left(\frac{Q}{g^{\frac{1}{2}}*h_e^{\frac{5}{2}}}\right)$ and $(\frac{T}{h_e})$ for same radius and thicknesses mentioned up.

It is observed from the figures that the relationship between the dimensionless parameter and $(\frac{T}{h_e})$ is a direct relationship.

Also, it is noticed from these figures that the discharge increases with the increment of the weir's thickness until 1.2 cm, after it the discharge value starts to decrease.

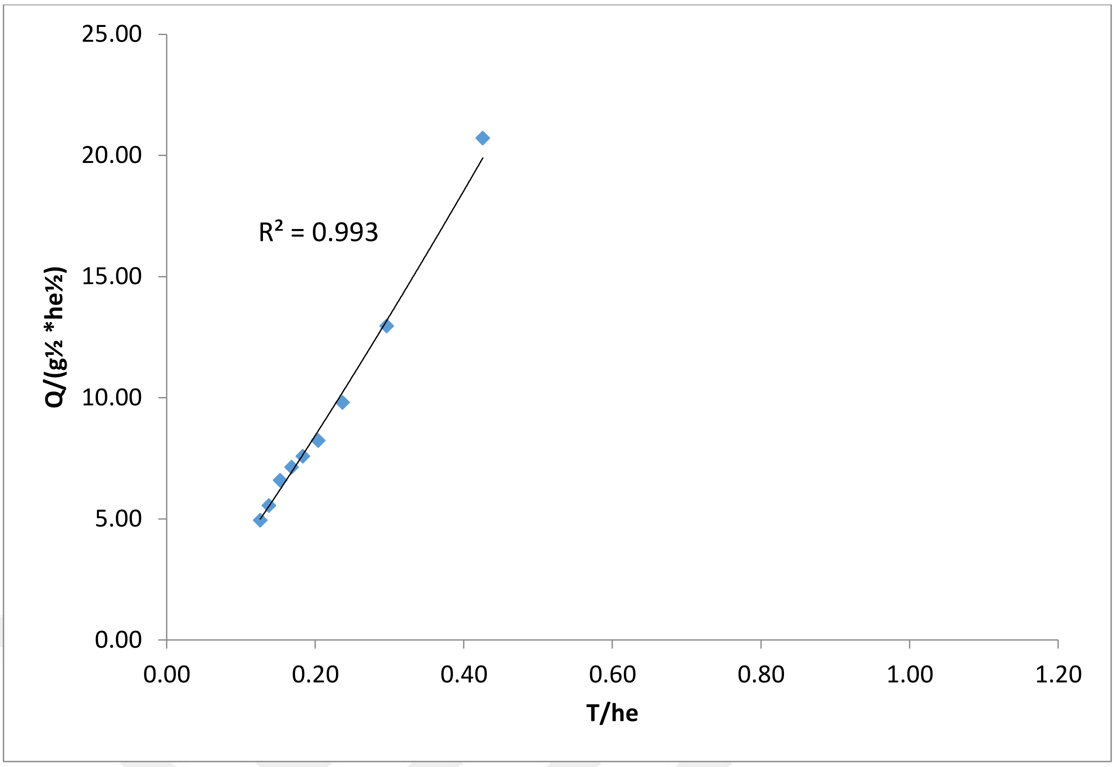

Figure 4.26 Relationship between $\left(\frac{Q}{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}\right)$ and $(\frac{T}{h_e})$ when T= 0.4 m and R = 25 cm

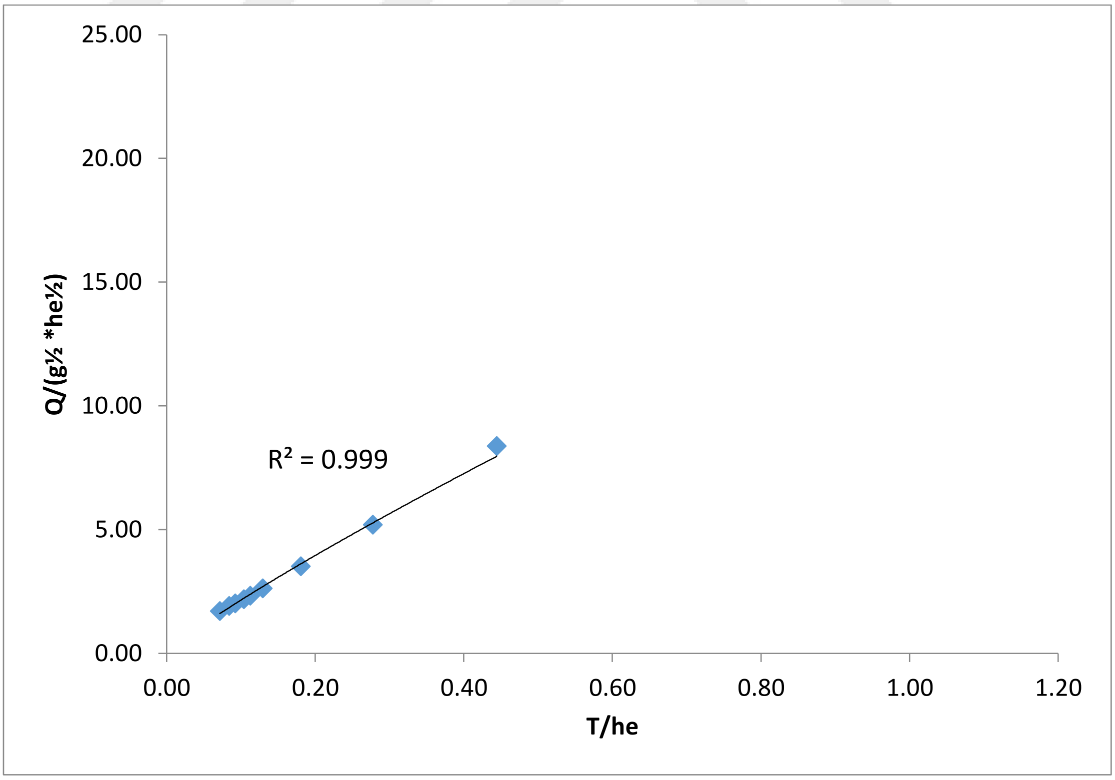

Figure 4.27 Relationship between $\left(\frac{Q}{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}\right)$ and $(\frac{T}{h_e})$ when T= 0.8 cm and R = 25 cm

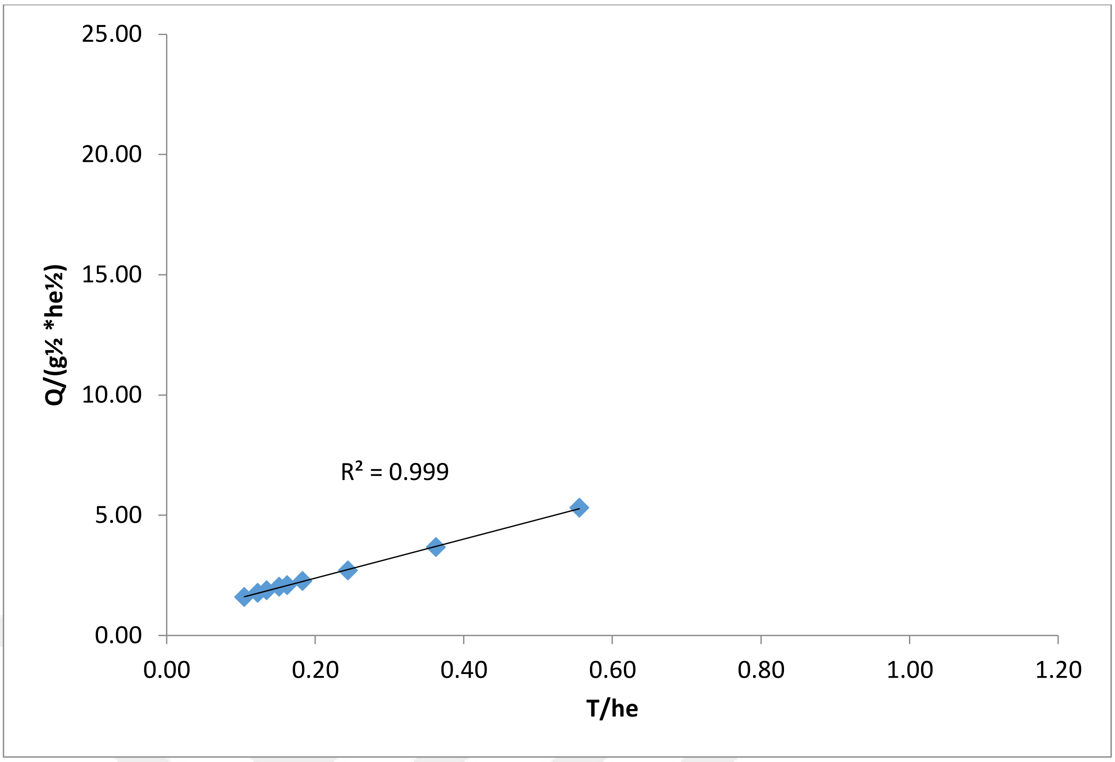

Figure 4.28 Relationship between $\left(\frac{Q}{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}\right)$ and $(\frac{T}{h_e})$ when T= 1.2 cm and R = 25 cm

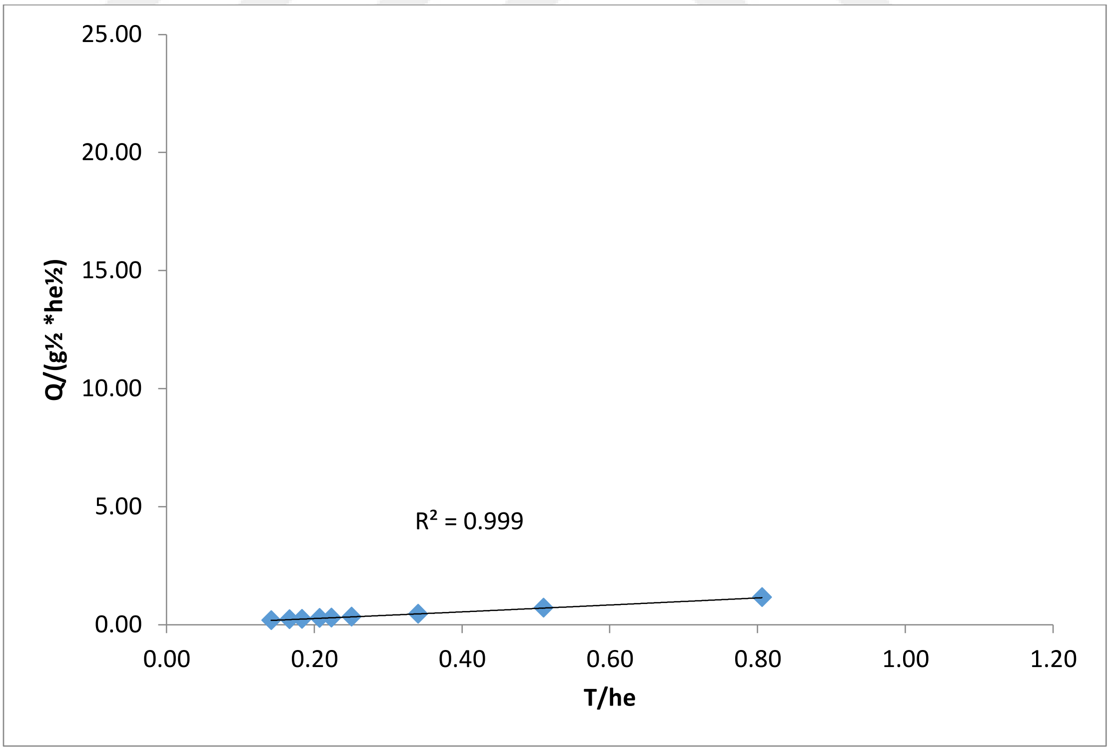

Figure 4.29 Relationship between $\left(\frac{Q}{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}\right)$ and $(\frac{T}{h_e})$ when T= 1.6 cm and R = 25 cm

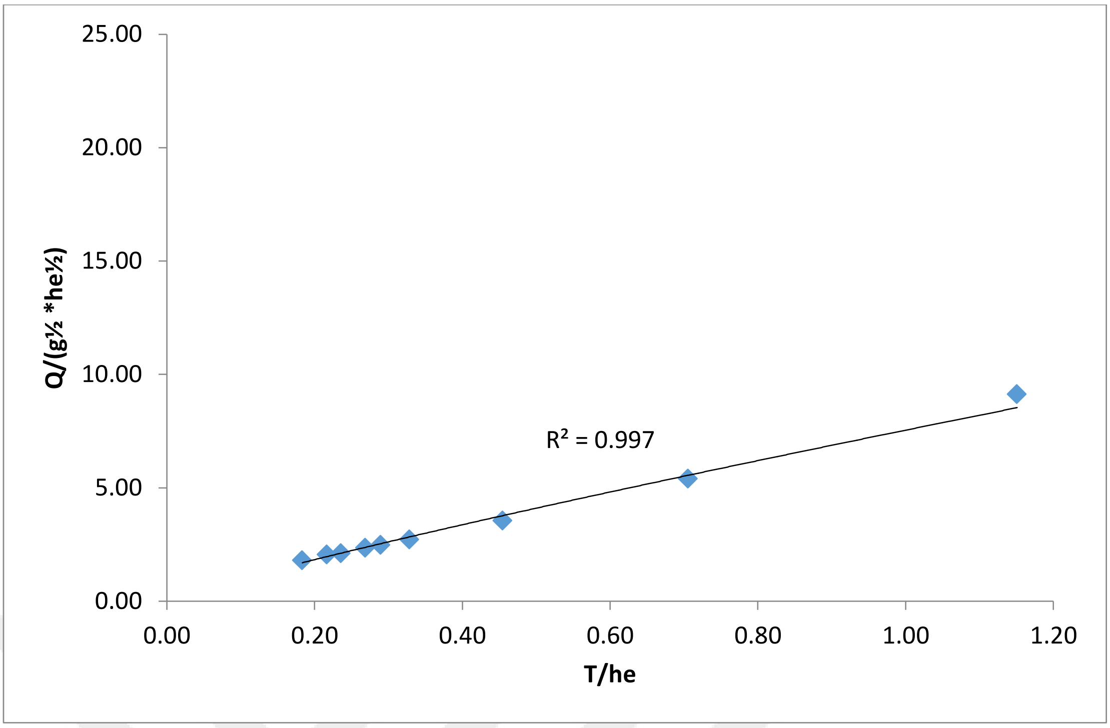

Figure 4.30 Relationship between $\left(\frac{Q}{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}\right)$ and $(\frac{T}{h_e})$ when T= 2 cm and R = 25 cm

Finally, the average thickness effect ratios of the discharge over weir's crest (from weir with a certain thickness to another one) were arranged as in Table 4.16:

Table 4.16 Average thickness effect ratios on discharge over weirs

NO.	Thickness (cm)	Semi-circular weirs R = 15 cm	Semi-circular weirs R = 20 cm	Semi-circular weirs R = 25 cm	Result
1	0.4 – 0.8	10.33 %	12.17 %	12.61 %	Increasing
2	0.8 – 1.2	14.6 %	15.56 %	15.70 %	Increasing
3	1.2 – 1.6	6.31 %	6.89 %	9.57 %	Decreasing
4	1.6 - 2	9.97 %	11.93 %	16.02 %	Decreasing

4.2.2 Effect of Change in The Weir's Radius (R) on Discharge (Q)

Through analysis of the results of the experiments which used in this study showed that existence of effect of weir's radius change (R = 15, 20 and 25 cm) on the quantity of discharge with constant the thickness of the weir, therefore the relationships which explain effect of weir's radius change were plotted.

Figures 4.31 - 4.35 exhibit the relationship between the dimensionless parameter of discharge $\left(\frac{Q}{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}\right)$ and $(\frac{R}{h_e})$ at changing of weir's radius three times, using different heights for the edge of the weir = 35, 30 and 25 cm and with constant the thickness of the weir.

It is noted from the figures that the relationship between the dimensionless parameter and $(\frac{R}{h_e})$ between them is a direct relationship. in addition, it is noted from the figures below that the discharge increases with increment of the weir's radius.

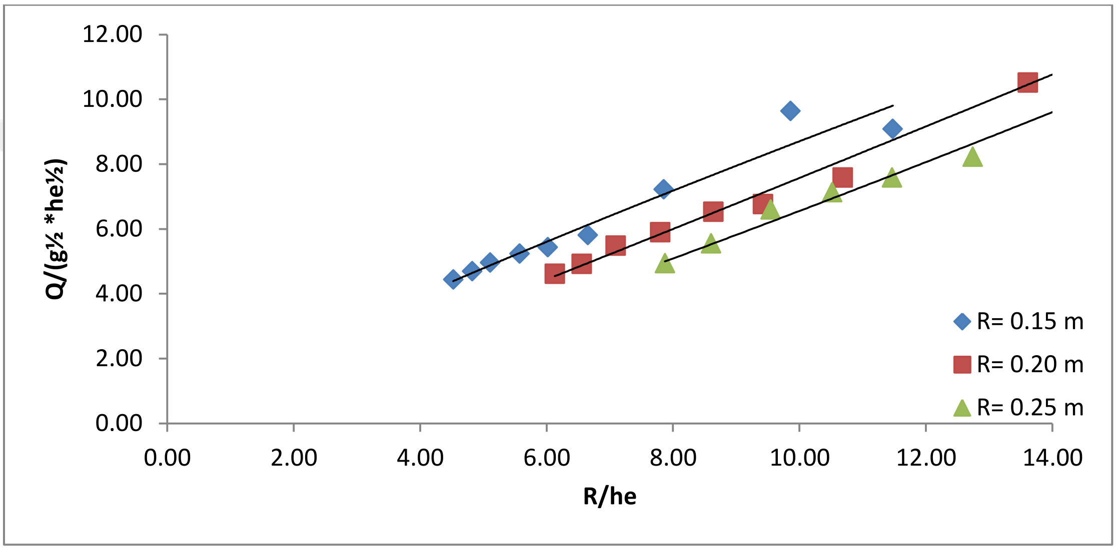

Figure 4.31 Relationship between $\left(\frac{Q}{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}\right)$ and $(\frac{R}{h_e})$ when T= 0.4 cm

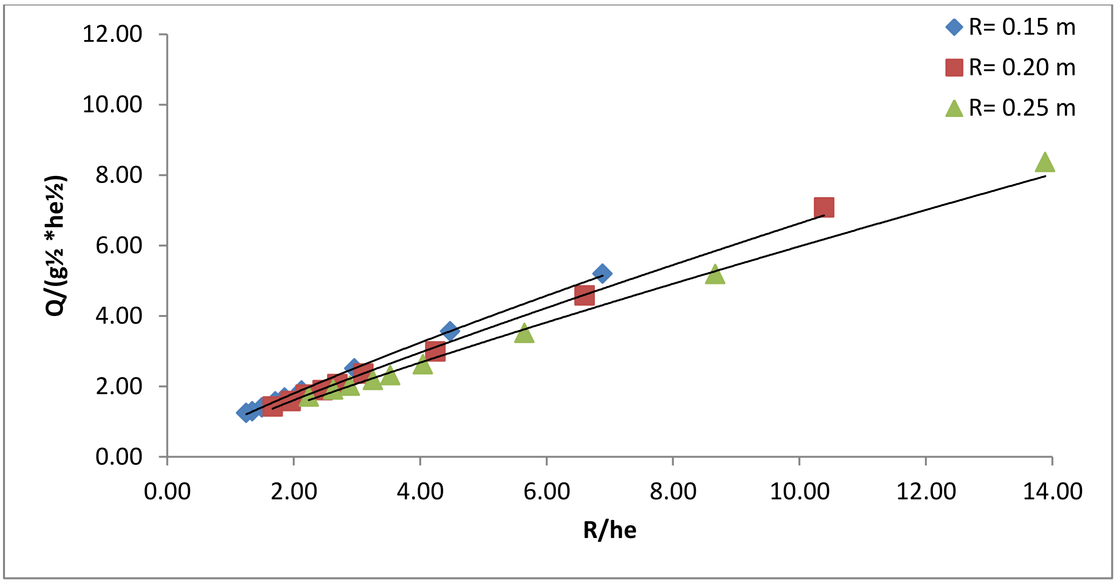

Figure 4.32 Relationship between $\left(\frac{Q}{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}\right)$ and $(\frac{R}{h_e})$ when T= 0.8 cm

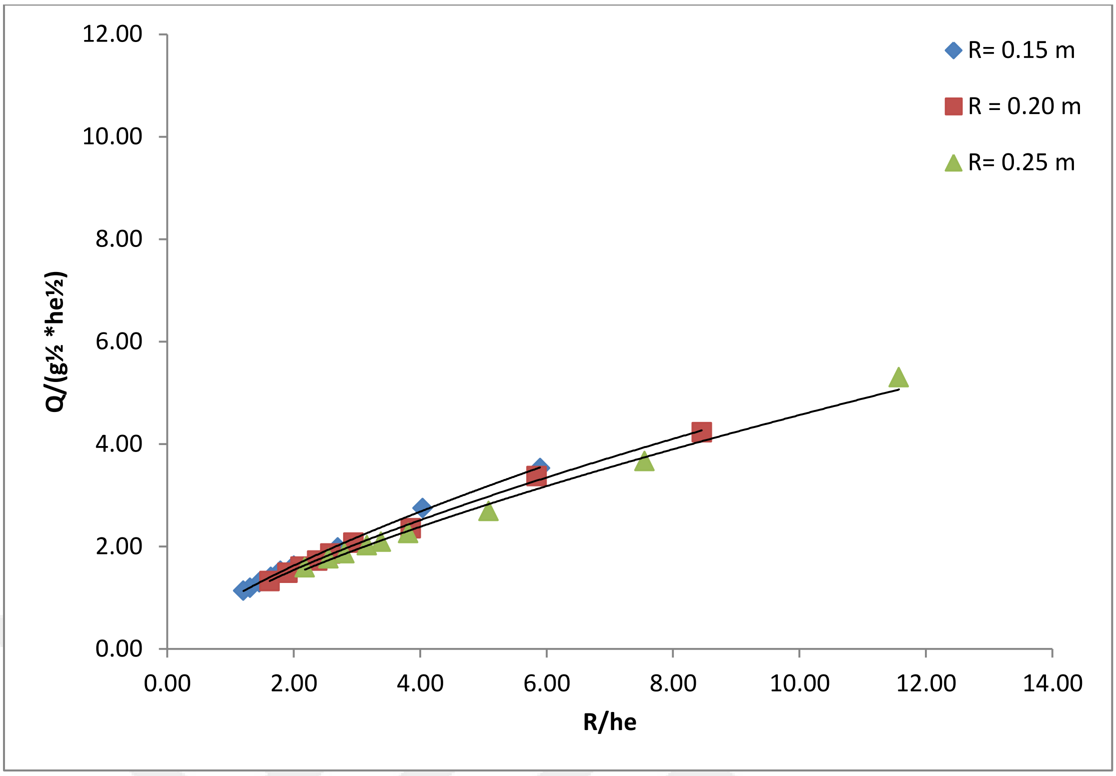

Figure 4.33 Relationship between $\left(\frac{Q}{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}\right)$ and $(\frac{R}{h_e})$ when T= 1.2 cm

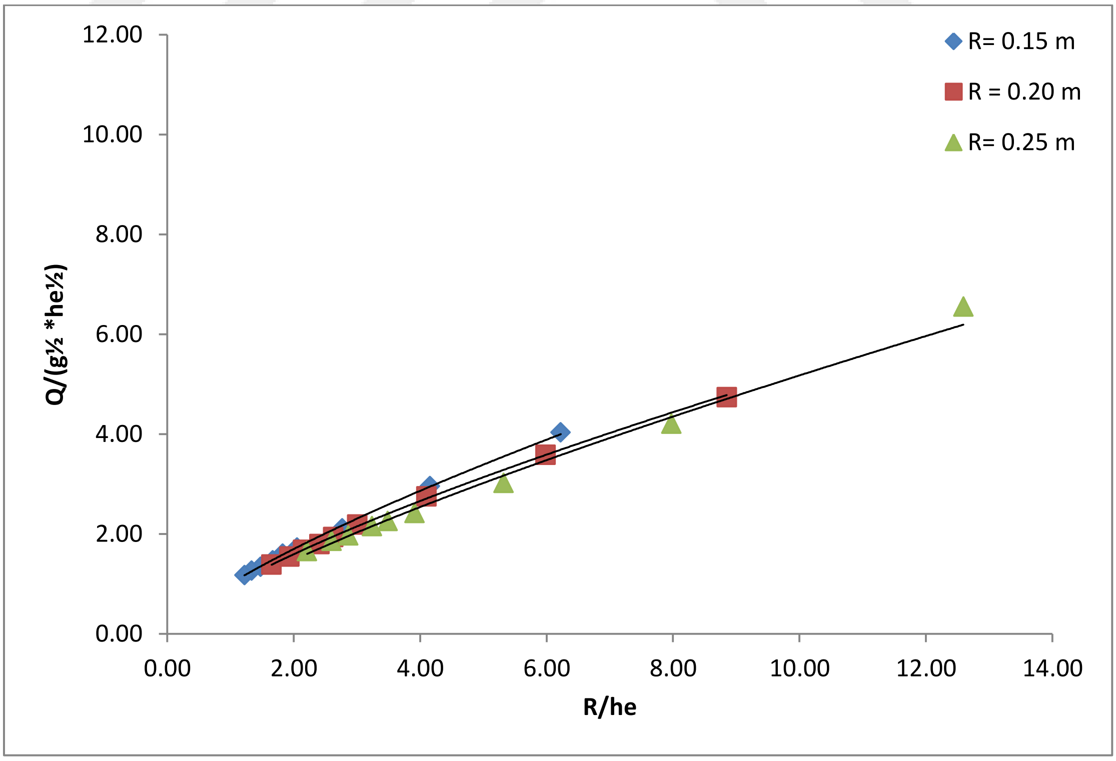

Figure 4.34 Relationship between $\left(\frac{Q}{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}\right)$ and $(\frac{R}{h_e})$ when T= 1.6 cm

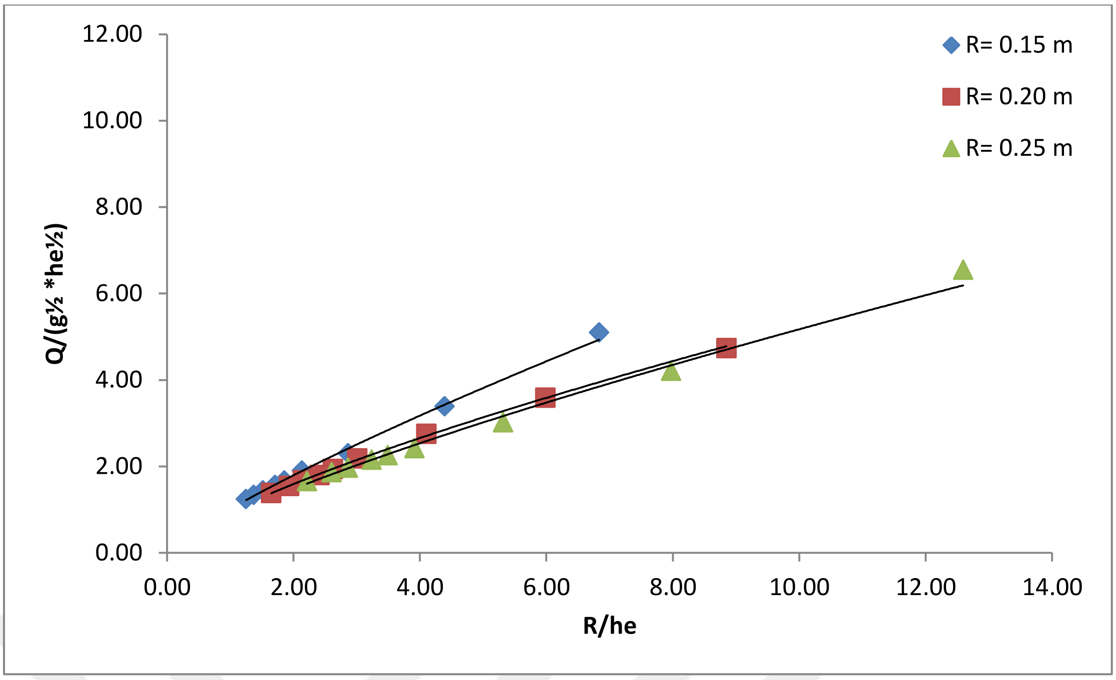

Figure 4.35 Relationship between $\left(\frac{Q}{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}\right)$ and $(\frac{R}{h_e})$ when T= 2 cm

From these figures we observed that whether the radius of weir increases, the quantity of discharge increasing as well. To clarify these situations as we noticed during experiments when the discharge equals 8.25 m^3/hr and the thickness of the weir (T) is 0.4 cm, the amount of water height over the weir h_e equals 29.4 mm when R is equal to 15 cm, while with R is 20 cm and at the same discharge, the height of the water is 28.28 mm. Also with R = 25 cm, the height of the water over the weir is 26.2 mm. The effect of changing the radius of weir's aperture on increasing the discharge value (Q) is in varying proportions. The overall increment ratio when the radius changes from 15 cm to 20 cm is 23.21%, which is greater than when the radius changes From 20 cm to 25 cm and was equal to 19.27%.

Figures 4.36 - 4.40 explain the relationship between the dimensionless parameter of discharge $\left(\frac{Q}{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}\right)$ and $(\frac{T}{h_e})$ at changing of weir's radius three times, and by using same the heights for the edge of the weir = 35, 30 and 25 cm and with constant also the thickness of the weir.

It is noted from Figures 4.36 – 4.40 below that the relationship between the dimensionless parameter and $(\frac{T}{h_e})$ between them also is a direct relationship. In addition, it is noted that the discharge increases with increment of the weir's radius.

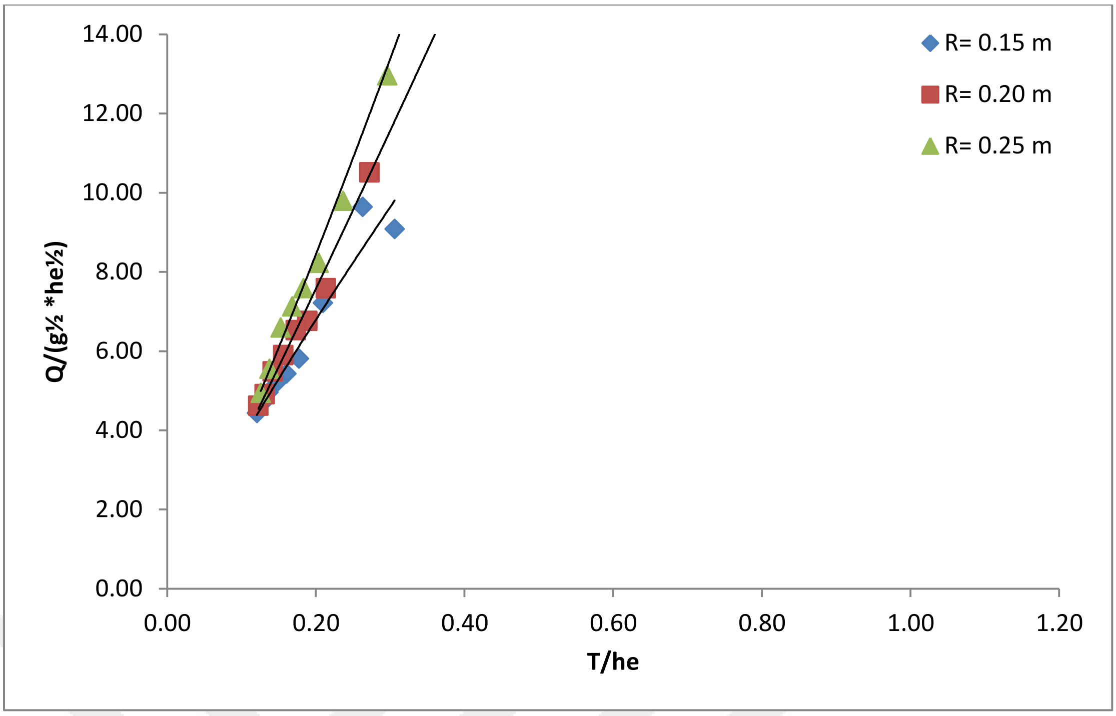

Figure 4.36 Relationship between $\left(\frac{Q}{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}\right)$ and $(\frac{T}{h_e})$ when T= 0.4 cm

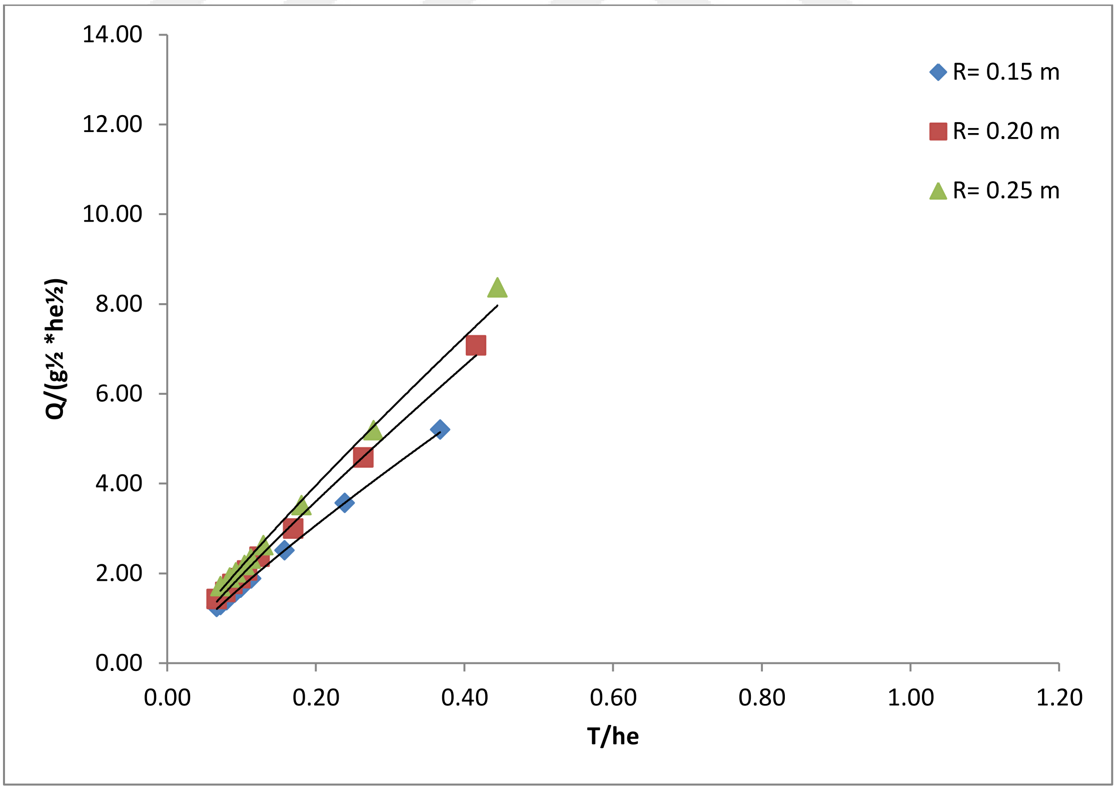

Figure 4.37 Relationship between $\left(\frac{Q}{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}\right)$ and $(\frac{T}{h_e})$ when T= 0.8 cm

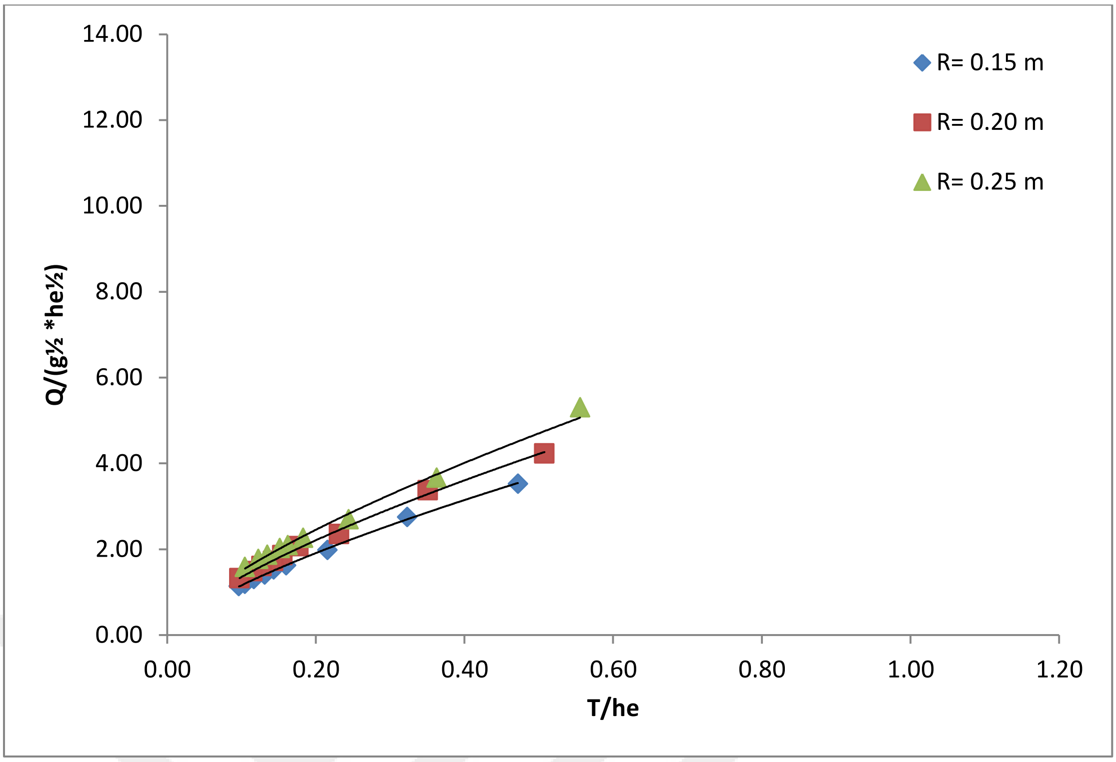

Figure 4.38 Relationship between $\left(\frac{Q}{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}\right)$ and $(\frac{T}{h_e})$ when T= 1.2 cm

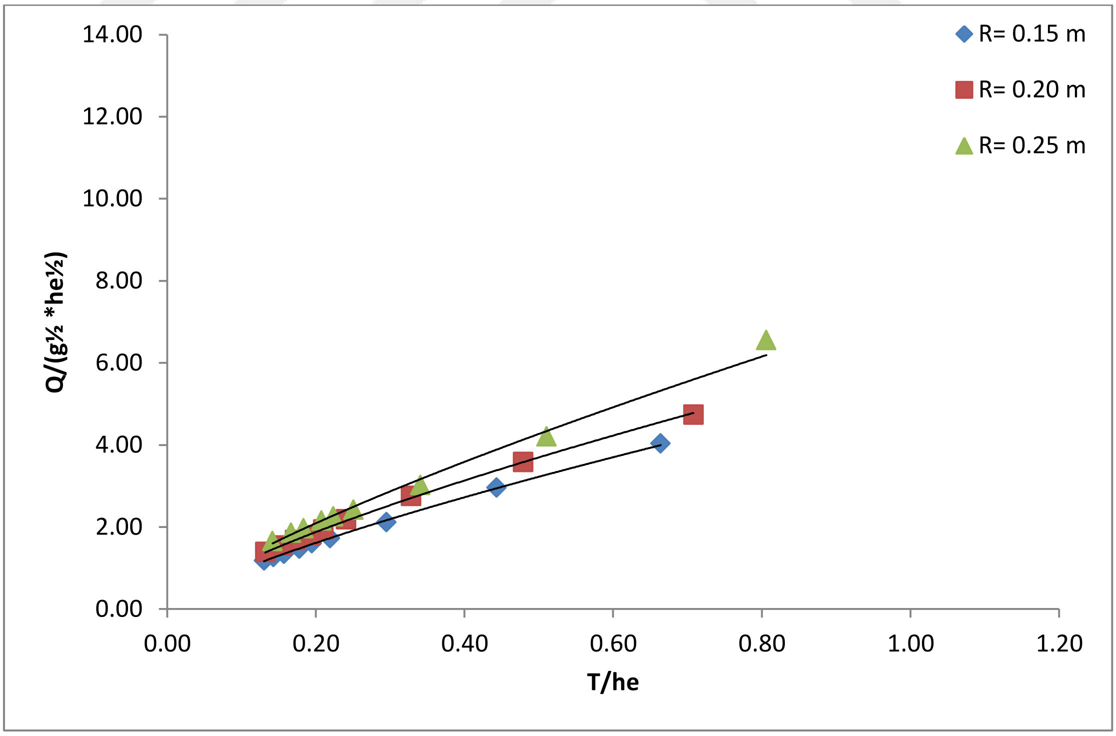

Figure 4.39 Relationship between $\left(\frac{Q}{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}\right)$ and $(\frac{T}{h_e})$ when T= 1.6 cm

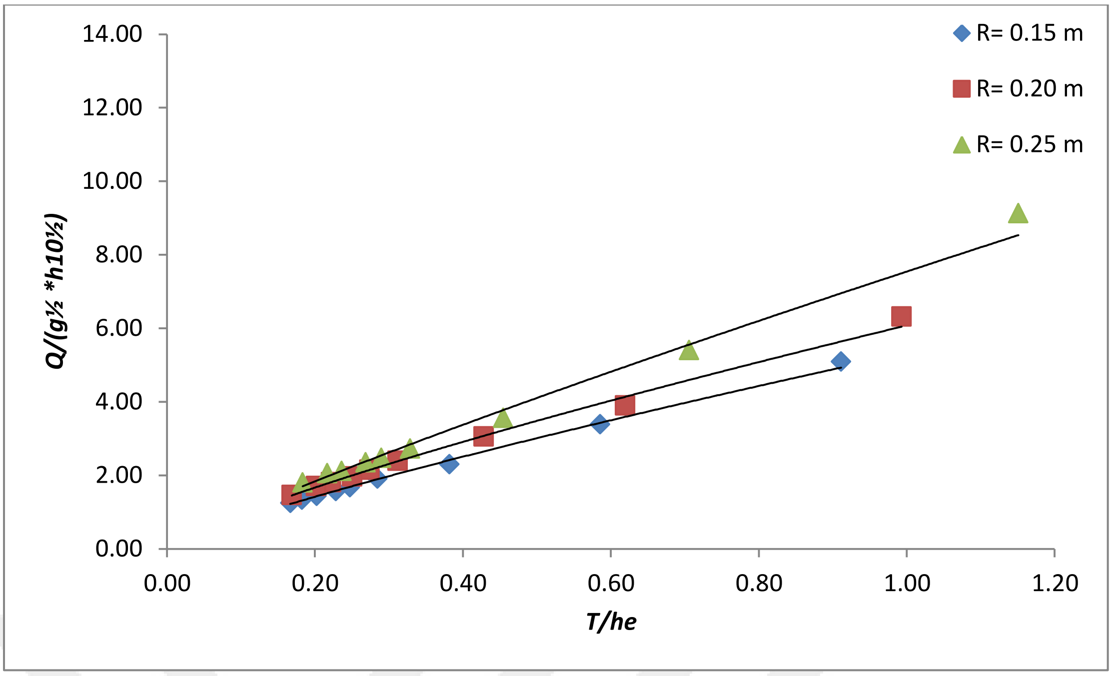

Figure 4.40 Relationship between $\left(\frac{Q}{g^{\frac{1}{2}} * h_e^{\frac{5}{2}}}\right)$ and $\left(\frac{T}{h_e}\right)$ when T= 2 cm

From Figures 4.36 – 4.40 observed that whether the radius of weir increasing, increases with its quantity of the discharge passed through it and that the effect of changing the radius of weir's aperture (R) on increasing the value of discharge (Q) is in varying proportions. The overall increment ratio when the radius R changes from 15 cm to 20 cm, is greater than when the radius changes from 20 cm to 25 cm.

4.3 Results of Statistical Analysis

Two statistical programs SPSS and Minitab, were used for the purpose of finding two empirical equations that calculate the discharge value of the flow over semi-circular weirs with semi-circular crest. Approximately 70% of the results were entered into these two programs, while the remaining 30% was used to compare the discharge value calculated by the extracted equations from the two programs and the laboratory results to ascertain the accuracy of these two equations.

4.3.1 Discharge Equation for Semi-circular Weirs with Semi-circular Edge by SPSS Program

An equation has been extracted to calculate the discharge for semi-circular weirs with semi-circular crest by nonlinear regression analysis using SPSS:

$$Q = 1.121 * (T)^{-0.204} * (P)^{0.420} * (R)^{0.705} * h_e^{1.579} \quad (4.1)$$

The determination coefficient value (R^2) for this equation is equal to 0.978. The accuracy of Equation 4.1 was tested in the discharge calculating by entering the recent 30 % of the laboratory data and calculate the predicted discharge. The results were plotted with the discharge measured in the laboratory.

Figure 4.41 compares the predictions of Equation 4.1 versus the experimental ones. It is observed that Equation 4.1 successfully predicted the discharge by $R^2 = 0.991$.

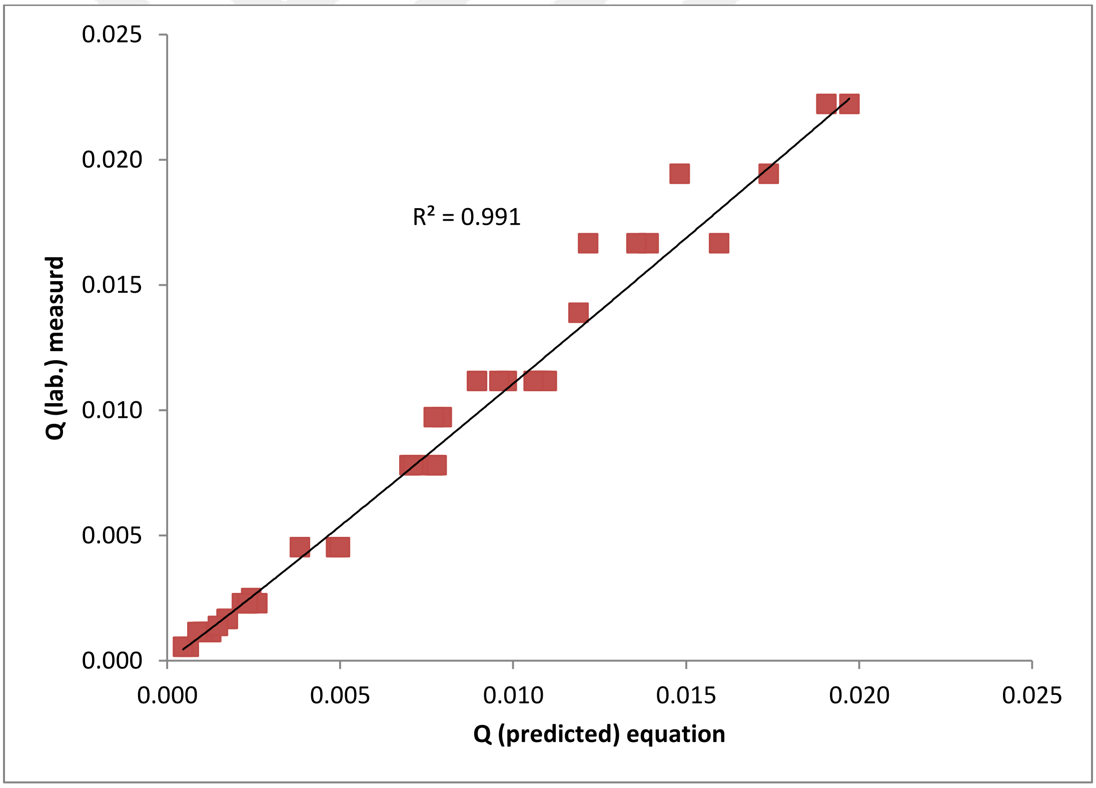

Figure 4.41 The scatter plot of the predicted discharge by the equation and the experimental discharge for SPSS results

4.3.2 Discharge Equation for Semi-circular Weirs with Semi-circular Edge by Regression Analysis

An equation has been extracted to calculate the discharge for semi-circular weirs with semi-circular crest by nonlinear regression analysis using Minitab software:

$$Q = \left[\left(1.42 * {h_e}^{2.5}\right) + \left((1.25R + 0.46P - 1.95T) * {h_e}^{1.5}\right) + \left((O.037R^2 + 0.028P^2 + 34.72T^2 - 1.35RT - 2.08PT) * {h_e}^{0.5}\right)\right] \quad (4.2)$$

The determination coefficient value (R^2) for this equation is equal to 0.995. The accuracy of Equation 4.2 was tested in the discharge calculating by entering the recent 30 % of the laboratory data and calculate the predicted discharge. The results were plotted with the discharge measured in the laboratory as well.

Figure 4.42 compares the predictions of Equation 4.2 versus the experimental ones. It is observed that Equation 4.2 successfully predicted the discharge by $R^2 = 0.996$.

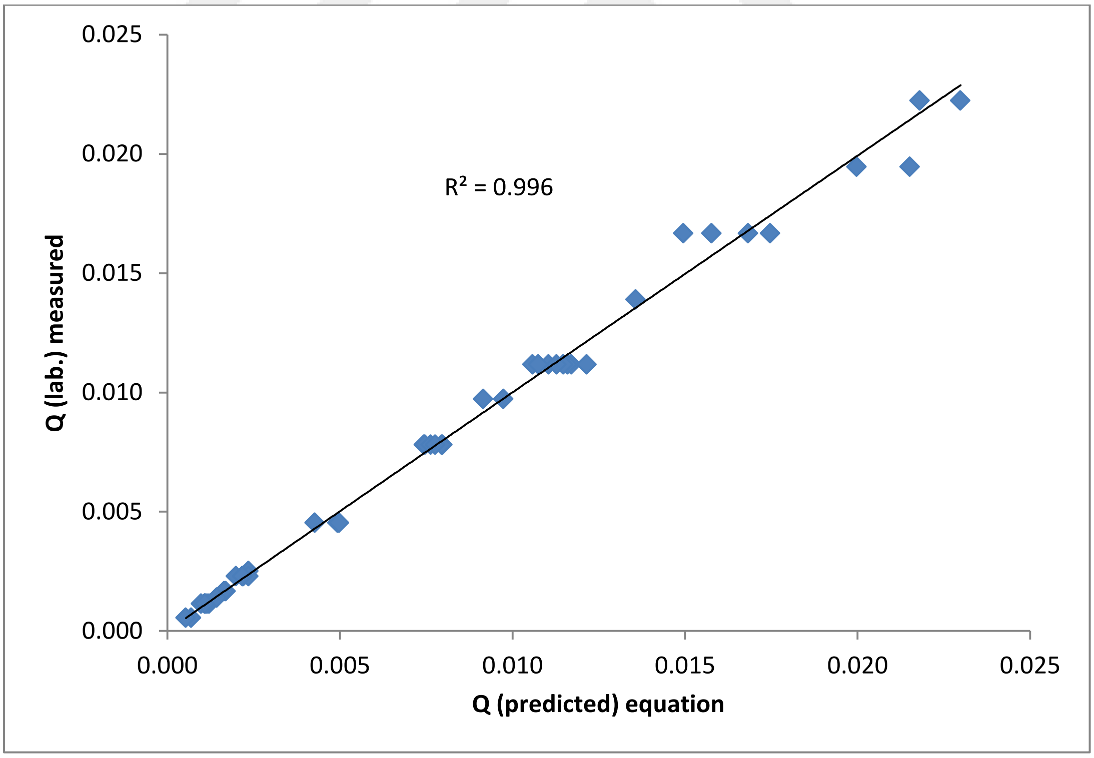

Figure 4.42 The scatter plot of the predicted discharge by the equation and the experimental discharge for Minitab results

4.4 Analysis of the Results by ANN Technique

4.4.1 ANN Theory

An Artificial Neural Network (ANN) is an information processing paradigm that is inspired by the way biological nervous systems, such as the brain, process information. The key element of this paradigm is the novel structure of the information processing system. It is composed of a large number of highly interconnected processing elements (neurons) working in harmony to solve specific problems. ANN, like people, learn by example. An ANN is configured for a specific application, such as pattern recognition or data classification, through a learning process. Learning in biological systems involves adjustments to the synaptic connections that exist between the neurons. This is true for ANNs as well.[31]

The complexity of real neurons is highly abstracted when modelling artificial neurons. These basically consist of inputs (like synapses), which are multiplied by weights (strength of the respective signals), and then computed by a mathematical function which determines the activation of the neuron (See Figure 4.43). Another function (which may be the identity) computes the output of the artificial neuron (sometimes in dependence of a certain threshold). ANN combine artificial neurons in order to process information.[32]

Further information on ANN technique can be found in Guven et al.(2006), Guven and Gunal (2008), Guven et al.(2017).[33,34,35]

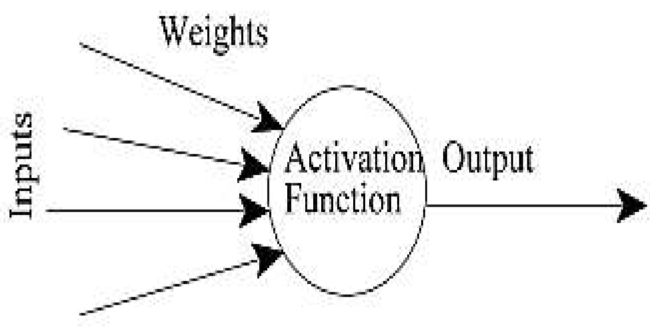

Figure 4.43 An artificial neuron

4.4.2 Obtaining Results by ANN

After finding the equation for the semi-circular weirs with semi-circular crest, the obtained data from the experiments were used for analysis by the Artificial Neural Network ANN technique with SPSS software for the purpose of determining which factors have the greatest influence on the properties of flow over semi-circular weirs with semi-circular crest. It was found that the radius of the weir's aperture (R) was the most important factor in its effect on the flow over this type of weirs. The effect was 31.93 %, and the less effect is the thickness of weir 11.7 %, as shown in Table 4.16 and Figure 4.44 below:

Table 4.17 The percentage for factors effecting on flow

NO.	Factor	Ratio (%)
1	R	31.93
2	P	30.3
3	T	11.7

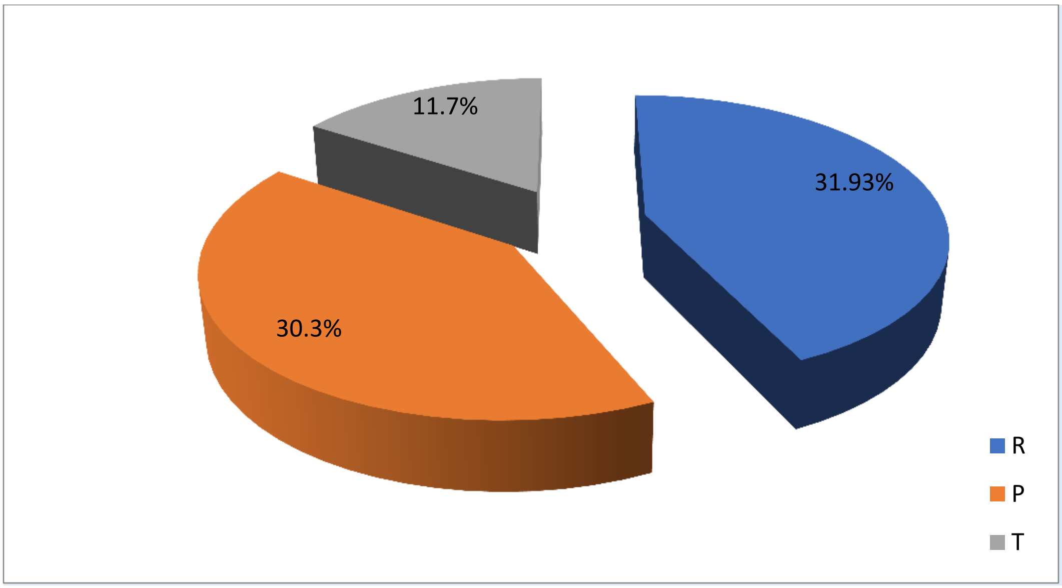

Figure 4.44 The percent ratios for three factors which effect on flow over semi-circular weirs with semi-circular crest

4.5 Obtaining the Critical Thickness

After obtaining the experimental results in laboratory and conducting the necessary calculations, we observed that (Q) increases with the thickness 0.4 cm to the thickness 0.8 cm, and from the thickness of 0.8 cm to the thickness of 1.2 cm. It is noted that the height of water over the weir decreased when T = 1.6 cm as compared to the semi-circular weir with T = 1.2 cm and it continuous to decrease till T = 2 cm.

It can be understood that the critical thickness is bounded between 1.2 and 1.6 cm, therefore we proposed three additional models of semi-circular weir with semi-circular crest with thickness 1.4 cm and three radii of 15, 20 and 25 cm. The laboratory experiments were conducted on the weir's thickness 1.4 cm because the material of laboratory-manufactured models can provide this medium thickness. Tables B.1 to B.3 in the Appendix B represent the results related to this experiments. Where it was observed that the discharge varies from Q = 8.47 m^3/hr at T = 1.2 cm to Q = 8.27 m^3/hr at T = 1.4 cm with constant R = 20 cm, through observing decreasing of the height of the water over weir's edge at the thickness 1.4 cm, as shown in Tables B.1 - B.3 in Appendix B. These tables show the specific calculations related to the obtained laboratory results.

The value of the critical thickness was determined exactly by interpolation using the experimental data of the semi-circular weir with semi-circular crest with the radius of 15 cm and the height of 35 cm and it was equal to 1.21 cm, as shown in Table 4.17 and Figure 4.45:

Table 4.18 determination of critical thickness for semi-circular weirs with semi-circular crest, weir's thickness (T), the radius R = 15 cm and the height P = 35 cm.

NO.	R (cm)	P (cm)	Q (m^3/hr)	T (mm)	h_e (mm)
1	15	35	8.25	4	29.4
2			8.25	8	33.50
3			8.25	12	37.20
4			8.25	16	36.10
5			8.25	20	34.20
6			8.25	14	37.00
7			8.25	13	37.10
8			8.25	12.5	37.15
9			8.25	**12.1**	**37.19**
10			8.25	12.2	37.18
11			8.25	12.3	37.17
12			8.25	12.4	37.16

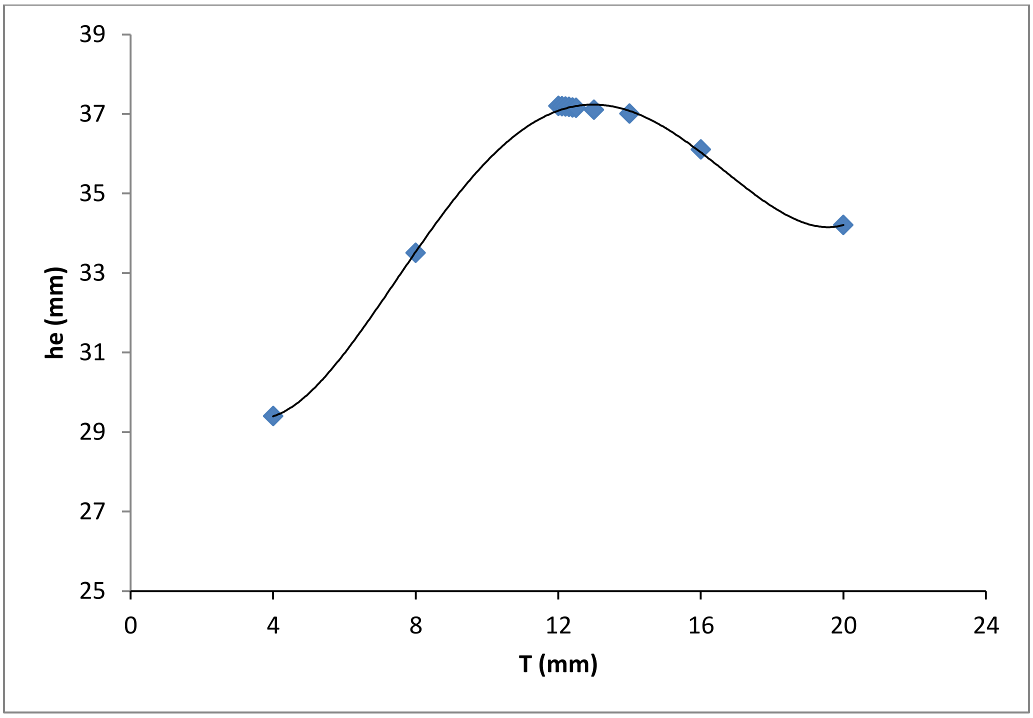

Figure 4.45 Clarification the effect of the thickness on the water height over crest especially critical thickness

CHAPTER 5

CONCLUSIONS

5.1 Conclusions

In present study, the hydraulic characteristics of the flow over semi-circular weir with semi-circular crest were studied and analyzed statistically by using the results obtained from experiments.

162 experiments were conducted on 18 models to observe the effect of the thickness and the radius of the weir's aperture on the discharge over the weir crest.

The following results drawn from this thesis may be listed as follows:

- The current study shows that the thickness of the weir (T) is one of the factors influencing the discharge, where the discharge increases with the increasing thickness with constant radius and the height of weir's edge. But this increment stops on certain limits as in our current study stopped the increment in discharge until reaching the thickness value of 12.1 mm and then begins to decline gradually, which is called the critical thickness.
- The other two factors are the radius of weir R, and the height of weir P. They also have a direct effect on the amount of discharge, noting that this effect is slightly greater for the height of the edge of the weir compared with it and much larger compared to thickness.
- The effect of change in the thickness of weir on increasing the value of the discharge (Q) is in varying proportions. The increment ratio will be at when the thickness changes from 0.4 cm to 0.8 cm and the increment ratio is greater when the thickness changes from 0.8 cm to 1.2 cm. The discharge after the thickness 1.21 cm starts to decrease. The decrement ratio began from thickness of 1.21 cm to 1.6 cm and it is greater when the thickness changes from 1.6 cm to 2 cm.

- The critical thickness value of the weir within the design dimensions of the models under study is equal to 12.1 mm precisely where discharge stops in increasing by increasing the thickness of the weir at this value and then the discharge starts decreasing thereafter, which represents an important value taken into consideration for design purposes.
- The highest discharge value obtained (Q = 79.98 m^3/hr) when the thickness was 1.2 cm and the radius of weir's aperture is 25 cm.
- The radius of weir and the height of weir's crest influence are directly proportional to the increase in the amount of discharge, noted that this effect is slightly larger for the height of the crest of the weir compared with it and is much larger compared with the thickness.
- Reliable empirical equations have been obtained based on the results of the dimensional analysis and the application of 70 % of the laboratory results in the two statistical programs SPSS and Minitab softwares, to calculate the discharge over semi-circular weir with semi-circular crest. 30 % of the data were used for testing purpose.
- Based on the analysis of the results by ANN technique, it was found that the most important variables affecting on the flow over the semi-circular weirs with a semi-circular crest is the radius of the weir's aperture R, where the ratio of its effect is about 31.93 %. secondly the effect of the height of the edge of the weir P and the impact rate is 30.3 %. Finally, comes the effect of weir's thickness T with an impact ratio of 11.7 %.

5.2 Recommendation for Further study

Based on as mentioned earlier and what has been reached in this study, the following studies can be recommended:

- The effect of the thickness of the weir on the characteristics of flow over other forms of weirs, such as rectangular, triangular or trapezoidal weirs can be studied.
- New experimental runs can be performed to illustrate the effect of the relationship between the increment of the radius of weir with constant the value of the critical thickness to determine whether the discharge continues to increase in this case or it stops at a specific radius can also be called critical radius.
- It is recommended to study the flow characteristics of the weirs used in this study using computational fluid dynamics (CFD) softwares or any other method of theoretical analytical methods and compare with the results of the current study.

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APPENDIX

Appendix (A)

Table A.1 Laboratory results of flow over semi-circular weirs with semi-circular crest, weir's thickness T = 0.4 cm, the aperture's radius R = 15 cm and the height of weir's edge P = 35 cm

No.	R = 15 cm				P = 35 cm			T = 0.4 cm			
	Q_i (m^3/hr)	h_1 (mm)	h_2 (mm)	h_3 (mm)	h_4 (mm)	h_5 (mm)	h_6 (mm)	h_7 (mm)	h_8 (mm)	h_9 (mm)	h_{10} (mm)
1	2	10.59	10.77	10.91	11.20	11.35	11.66	12.16	12.47	12.82	13.07
2	3.10	11.33	11.72	11.94	12.09	12.43	12.89	13.91	14.51	14.99	15.21
3	4.10	15.31	15.54	15.88	16.12	16.38	17.51	18.03	18.36	18.79	19.10
4	5	18.73	18.99	19.19	19.43	19.75	20.22	20.53	21.37	21.89	22.55
5	6	21.95	22.12	22.51	22.82	23.08	23.31	23.79	24.15	24.49	24.92
6	7	23.89	23.97	24.18	24.55	25.30	25.70	26.11	26.34	26.66	26.90
7	8.25	25.86	26.10	26.32	26.75	27.15	27.37	28.05	28.49	28.89	29.35
8	9	27.10	27.34	27.75	27.99	28.50	29.43	30.30	30.61	30.95	31.08
9	10	29.19	29.51	29.86	30.16	30.39	30.95	31.66	32.27	32.78	33.15

Table A.2 Laboratory results of flow over semi-circular weirs with semi-circular crest, weir's thickness T = 0.8 cm, the aperture's radius R = 15 cm and the height of weir's edge P = 35 cm

No.	R = 15 cm				P = 35 cm			T = 0.8 cm			
	Q_i (m^3/hr)	h_1 (mm)	h_2 (mm)	h_3 (mm)	h_4 (mm)	h_5 (mm)	h_6 (mm)	h_7 (mm)	h_8 (mm)	h_9 (mm)	h_{10} (mm)
1	4.10	16.95	17.69	18.05	18.44	18.81	19.25	19.65	20.16	20.77	21.78
2	8.25	26.90	27.55	28.28	28.50	28.80	29.33	29.67	30.18	30.49	33.50
3	16.30	46.65	47.68	48.20	48.63	50.12	50.16	50.44	50.55	50.61	50.63
4	28.10	65.42	66.49	67.26	67.39	68.21	68.88	68.97	69.70	70.00	70.66
5	35	77.50	78.24	78.86	79.27	79.75	79.90	80.14	80.25	80.73	80.76
6	40.20	83.60	84.91	85.33	85.69	86.42	86.54	86.87	87.20	87.57	87.69
7	50	95.02	95.33	96.17	96.52	96.88	98.50	99.07	99.38	100.11	100.23
8	60	107.62	108.95	109.27	109.39	109.98	110.15	110.61	111.03	111.19	111.40
9	70	116.31	116.60	117.24	117.53	117.91	118.33	118.70	119.45	119.81	120.05

Table A.3 Laboratory results of flow over semi-circular weirs with semi-circular crest, weir's thickness T = 1.2 cm, the aperture's radius R = 15 cm and the height of weir's edge P = 35 cm**.**

No.	R = 15 cm				P = 35 cm			T = 1.2 cm			
	Q_i (m^3/hr)	h_1 (mm)	h_2 (mm)	h_3 (mm)	h_4 (mm)	h_5 (mm)	h_6 (mm)	h_7 (mm)	h_8 (mm)	h_9 (mm)	h_{10} (mm)
1	4.10	22.31	22.69	23.11	23.48	23.77	24.16	24.56	24.84	25.07	25.43
2	8.25	32.80	32.91	33.25	34.21	35.34	35.48	35.66	36.41	36.98	37.15
3	16.30	51.88	51.93	52.44	53.13	53.90	53.98	54.35	54.94	55.06	55.65
4	28.10	70.77	70.97	71.36	72.95	73.01	73.16	73.40	73.44	74.92	74.95
5	35	80.56	81.14	81.67	82.12	82.76	82.95	83.30	83.42	83.80	83.87
6	40.20	87.97	88.17	88.58	89.23	89.68	90.15	90.61	90.85	91.51	91.58
7	50	99.06	99.53	99.80	99.96	100.91	101.36	102.49	102.80	102.90	103.04
8	60	110.96	111.39	111.51	111.61	113.45	113.76	113.83	113.99	114.69	114.75
9	70	121.23	121.68	121.95	122.19	122.43	122.77	123.11	123.27	123.90	124.47

Table A.4 Laboratory results of flow over semi-circular weirs with semi-circular crest, weir's thickness T = 1.6 cm, the aperture's radius R = 15 cm and the height of weir's edge P = 35 cm

No.	R = 15 cm				P = 35 cm			T = 1.6 cm			
	Q_i (m^3/hr)	h_1 (mm)	h_2 (mm)	h_3 (mm)	h_4 (mm)	h_5 (mm)	h_6 (mm)	h_7 (mm)	h_8 (mm)	h_9 (mm)	h_{10} (mm)
1	4.10	21.76	21.89	22.12	22.53	22.78	23.24	23.47	23.69	23.98	24.10
2	8.25	30.85	31.95	32.33	32.76	33.09	33.65	34.75	35.52	35.93	36.10
3	16.30	50.79	50.90	51.00	52.02	52.30	52.76	52.87	53.31	53.72	54.23
4	28.10	69.01	70.11	70.75	71.50	71.91	72.18	72.35	72.60	72.88	73.10
5	35	79.26	79.65	80.13	80.61	80.92	81.10	81.25	81.47	81.69	82.21
6	40.20	86.43	86.77	87.20	87.55	87.79	88.46	88.62	88.94	89.25	89.93
7	50	98.07	98.59	99.68	99.89	100.52	101.03	101.12	101.60	101.73	101.78
8	60	108.95	109.41	109.59	109.87	110.31	110.70	110.91	111.28	111.51	112.20
9	70	118.88	119.21	119.73	120.09	120.37	120.86	121.41	121.78	122.49	122.80

Table A.5 Laboratory results of flow over semi-circular weirs with semi-circular crest, weir's thickness T = 2 cm, the radius R = 15 cm and the height of weir's edge P = 35 cm

No.	R = 15 cm				P = 35 cm			T = 2 cm			
	Q_i (m^3/hr)	h_1 (mm)	h_2 (mm)	h_3 (mm)	h_4 (mm)	h_5 (mm)	h_6 (mm)	h_7 (mm)	h_8 (mm)	h_9 (mm)	h_{10} (mm)
1	4.10	18.61	18.93	19.05	19.41	19.87	20.09	20.36	20.79	21.11	21.95
2	8.25	28.12	29.44	31.36	31.75	32.16	32.64	33.23	33.59	33.75	34.17
3	16.30	48.14	48.93	49.09	49.27	49.63	50.43	50.56	50.92	51.55	52.40
4	28.10	66.06	67.09	67.18	67.26	67.63	68.70	68.94	69.11	69.46	70.29
5	35	78.13	78.29	78.77	79.24	79.41	79.66	79.84	80.37	80.86	80.90
6	40.20	84.61	85.32	85.55	85.63	86.39	86.60	86.78	87.57	87.65	87.70
7	50	95.39	95.51	95.90	96.33	96.81	97.16	97.64	97.68	97.76	98.92
8	60	105.13	106.23	106.62	107.14	108.05	108.49	108.71	109.55	109.57	109.66
9	70	115.75	116.31	116.59	116.88	117.16	118.22	118.35	118.63	119.44	120.10

Table A.6 Laboratory results of flow over semi-circular weirs with semi-circular crest, weir's thickness T = 0.4 cm, the aperture's radius R = 20 cm and the height of weir's edge P = 30 cm

No.	R = 20 cm				P = 30 cm			T = 0.4 cm			
	Q_i (m^3/hr)	h_1 (mm)	h_2 (mm)	h_3 (mm)	h_4 (mm)	h_5 (mm)	h_6 (mm)	h_7 (mm)	h_8 (mm)	h_9 (mm)	h_{10} (mm)
1	2	7.61	8.00	8.39	8.85	8.99	9.10	9.56	9.75	10.19	10.61
2	3.10	9.83	10.05	10.76	10.97	11.59	12.55	13.79	14.46	14.67	14.69
3	4.10	14.65	14.92	15.08	15.61	16.50	17.09	17.22	17.56	18.15	18.72
4	5	17.51	17.71	17.90	18.33	18.59	19.06	19.81	20.34	20.86	21.22
5	6	20.11	20.45	20.68	21.39	21.77	22.18	22.43	22.70	22.98	23.15
6	7	22.09	22.51	22.86	23.18	23.49	24.19	24.65	25.07	25.39	25.64
7	8.25	24.66	24.94	25.15	25.43	25.90	26.33	26.76	27.55	27.96	28.20
8	9	26.08	26.59	26.83	27.04	27.04	27.49	27.74	28.69	29.41	30.50
9	10	27.95	28.14	28.57	28.91	29.19	29.53	30.64	31.40	31.85	32.62

Table A.7 Laboratory results of flow over semi-circular weirs with semi-circular crest, weir's thickness T = 0.8 cm, the aperture's radius R = 20 cm and the height of weir's edge P = 30 cm

No.	R = 20 cm				P = 30 cm			T = 0.8 cm			
	Q_i (m^3/hr)	h_1 (mm)	h_2 (mm)	h_3 (mm)	h_4 (mm)	h_5 (mm)	h_6 (mm)	h_7 (mm)	h_8 (mm)	h_9 (mm)	h_{10} (mm)
1	4.10	15.50	16.01	17.02	17.43	18.67	18.70	18.89	19.00	19.21	19.25
2	8.25	26.15	27.32	28.05	28.44	28.67	29.22	29.46	29.94	30.01	30.30
3	16.30	44.41	44.75	45.38	45.86	46.61	46.98	47.00	47.08	47.14	47.17
4	28.10	61.85	62.51	62.77	63.09	63.79	64.01	64.14	64.21	64.39	64.43
5	35	71.85	72.37	72.43	72.79	73.10	73.45	73.70	73.96	74.17	74.35
6	40.20	79.25	79.33	79.70	80.07	80.46	80.65	80.77	80.94	80.98	81.41
7	50	88.41	88.66	88.82	89.36	90.20	90.32	90.63	91.00	91.33	91.38
8	60	99.56	99.82	100.73	100.85	101.46	101.77	101.88	102.13	102.40	102.48
9	80	117.07	117.93	118.17	118.29	118.88	119.01	119.12	119.52	119.90	120.00

Table A.8 Laboratory results of flow over semi-circular weirs with semi-circular crest, weir's thickness T = 1.2 cm, the aperture's radius R = 20 cm and the height of weir's edge P = 30 cm

No.	R = 20 cm				P = 30 cm			T = 1.2 cm			
	Q_i (m^3/hr)	h_1 (mm)	h_2 (mm)	h_3 (mm)	h_4 (mm)	h_5 (mm)	h_6 (mm)	h_7 (mm)	h_8 (mm)	h_9 (mm)	h_{10} (mm)
1	4.10	20.38	20.56	21.54	22.08	22.67	22.92	23.00	23.49	23.63	23.65
2	8.25	30.12	31.31	31.75	32.05	32.52	32.79	32.81	32.93	33.80	34.24
3	16.30	48.61	48.65	48.97	49.11	49.46	49.85	49.91	50.09	50.24	51.90
4	28.10	63.21	64.20	64.25	64.59	65.28	66.39	67.36	67.45	67.62	67.95
5	35	74.45	74.51	75.15	75.62	76.10	76.38	76.86	77.00	77.30	77.45
6	40.20	80.85	81.16	81.99	82.76	83.15	83.64	83.73	84.19	84.26	84.34
7	50	90.24	90.85	92.05	93.10	93.22	93.83	93.95	94.40	94.64	94.72
8	60	101.84	102.67	103.09	103.55	103.89	104.45	104.56	104.66	105.00	105.11
9	80	121.16	121.75	122.14	122.40	122.85	122.89	122.94	123.36	123.47	123.49

Table A.9 Laboratory results of flow over semi-circular weirs with semi-circular crest, weir's thickness T = 1.6 cm, the aperture's radius R = 20 cm and the height of weir's edge (P) = 30 cm

No.	R = 20 cm				P = 30 cm			T = 1.6 cm			
	Q_i (m^3/hr)	h_1 (mm)	h_2 (mm)	h_3 (mm)	h_4 (mm)	h_5 (mm)	h_6 (mm)	h_7 (mm)	h_8 (mm)	h_9 (mm)	h_{10} (mm)
1	4.10	19.33	19.95	20.09	20.22	20.97	21.21	21.32	21.44	21.79	22.60
2	8.25	29.83	30.11	31.33	31.77	32.08	32.50	32.78	32.81	32.95	33.42
3	16.30	46.13	46.64	46.87	47.34	47.56	47.81	48.05	48.32	48.45	48.77
4	28.10	62.31	63.70	64.51	64.75	64.87	65.69	65.84	65.96	66.23	66.52
5	35	73.88	74.15	74.46	74.85	75.57	75.77	75.90	76.02	76.13	76.19
6	40.20	80.04	80.70	81.11	81.18	81.49	81.95	82.38	82.45	82.86	83.00
7	50	89.77	90.26	90.61	91.50	91.63	92.03	92.15	92.44	93.00	93.05
8	60	100.87	100.94	101.31	101.89	102.14	102.37	102.64	102.92	103.12	103.46
9	80	119.25	119.82	120.17	120.45	120.88	120.93	120.98	121.10	121.24	121.30

Table A.10 Laboratory results of flow over semi-circular weirs with semi-circular crest, weir's thickness T = 2 cm, the aperture's radius R = 20 cm and the height of weir's edge P = 30 cm

No.	R = 20 cm				P = 30 cm			T = 2 cm			
	Q_i (m^3/hr)	h_1 (mm)	h_2 (mm)	h_3 (mm)	h_4 (mm)	h_5 (mm)	h_6 (mm)	h_7 (mm)	h_8 (mm)	h_9 (mm)	h_{10} (mm)
1	4.10	17.25	17.34	17.50	18.73	18.76	19.38	19.45	19.97	20.05	20.14
2	8.25	27.20	27.46	28.09	28.35	28.92	29.27	29.52	31.20	32.00	32.30
3	16.30	44.12	44.19	44.28	44.47	44.79	45.00	45.18	45.53	46.19	46.75
4	28.10	60.25	60.69	61.17	61.58	62.00	63.07	63.21	63.60	63.83	64.15
5	35	70.23	71.04	71.16	71.43	71.68	71.95	72.26	72.38	72.57	73.10
6	40.20	75.35	75.94	76.47	77.06	78.22	78.98	79.29	79.79	79.83	80.01
7	50	87.55	87.98	88.03	88.24	89.18	89.34	89.76	90.16	90.23	90.31
8	60	96.01	96.39	96.60	96.75	96.98	97.14	97.29	97.83	98.26	99.45
9	80	114.90	115.66	115.92	116.09	116.46	116.75	117.41	117.92	118.34	118.60

Table A.11 Laboratory results of flow over semi-circular weirs with semi-circular crest, weir's thickness T = 0.4 cm, the aperture's radius R = 25 cm and the height of weir's edge P = 25 cm

No.	R = 25 cm				P = 25 cm			T = 0.4 cm			
	Q_i (m^3/hr)	h_1 (mm)	h_2 (mm)	h_3 (mm)	h_4 (mm)	h_5 (mm)	h_6 (mm)	h_7 (mm)	h_8 (mm)	h_9 (mm)	h_{10} (mm)
1	2	6.78	6.95	7.07	7.11	7.32	8.10	8.51	8.64	9.02	9.40
2	3.10	8.33	9.12	9.66	10.21	10.76	11.18	11.49	12.57	12.84	13.51
3	4.10	13.04	13.35	13.67	14.13	14.29	14.81	15.05	15.62	16.25	16.90
4	5	15.31	15.60	15.93	16.11	16.27	16.45	17.10	17.46	18.79	19.62
5	6	18.38	18.77	19.05	19.61	20.20	20.46	21.10	21.35	21.59	21.80
6	7	20.30	20.67	20.94	21.25	21.44	22.51	22.89	23.18	23.52	23.77
7	8.25	22.02	22.36	22.71	23.20	23.76	24.90	25.53	25.74	26.00	26.19
8	9	25.70	25.93	26.22	26.56	27.30	27.82	28.11	28.52	28.87	29.05
9	10	27.10	27.79	28.37	28.74	29.51	30.17	30.49	30.80	31.29	31.75

Table A.12 Laboratory results of flow over semi-circular weirs with semi-circular crest, weir's thickness T = 0.8 cm, the aperture's radius R = 25 cm and the height of weir's edge P = 25 cm

No.	R = 25 cm				P = 25 cm			T = 0.8 cm			
	Q_i (m^3/hr)	h_1 (mm)	h_2 (mm)	h_3 (mm)	h_4 (mm)	h_5 (mm)	h_6 (mm)	h_7 (mm)	h_8 (mm)	h_9 (mm)	h_{10} (mm)
1	4.10	14.17	15.39	15.65	15.83	16.94	17.22	17.28	17.80	17.87	18.00
2	8.25	25.44	26.31	26.68	27.52	27.60	27.77	28.04	28.14	28.49	28.83
3	16.30	40.90	41.23	41.66	42.34	42.84	43.28	43.85	44.00	44.11	44.23
4	28.10	58.94	59.00	59.17	59.55	59.91	60.18	60.50	60.88	61.61	61.85
5	35	68.40	69.34	69.47	69.58	70.31	70.39	70.55	70.64	70.88	70.90
6	40.20	73.05	73.75	74.13	74.82	74.95	75.08	76.17	76.26	76.76	76.83
7	50	82.95	83.71	84.57	84.92	85.21	85.62	85.65	85.72	86.37	86.51
8	60	93.01	93.38	94.04	94.12	94.47	94.51	94.59	94.88	95.00	95.17
9	80	108.19	108.94	109.69	109.95	110.44	110.60	111.00	111.17	111.46	111.59

Table A.13 Laboratory results of flow over semi-circular weirs with semi-circular crest, weir's thickness T = 1.2 cm, the aperture's radius R = 25 cm and the height of weir's edge P = 25 cm

No.	R = 25 cm				P = 25 cm			T = 1.2 cm			
	Q_i (m^3/hr)	h_1 (mm)	h_2 (mm)	h_3 (mm)	h_4 (mm)	h_5 (mm)	h_6 (mm)	h_7 (mm)	h_8 (mm)	h_9 (mm)	h_{10} (mm)
1	4.10	17.71	18.80	18.95	19.72	19.97	20.33	20.53	20.84	21.15	21.60
2	8.25	30.08	30.65	31.02	31.29	31.78	31.90	32.17	32.48	32.83	33.11
3	16.30	45.20	45.29	45.67	46.04	47.16	47.33	47.85	48.36	48.96	49.19
4	28.10	61.75	62.62	62.83	63.21	64.01	64.10	64.19	64.30	65.48	65.60
5	35	70.14	70.77	71.09	71.80	72.29	72.78	72.85	73.56	73.75	73.92
6	40.20	76.52	77.08	77.39	77.46	78.31	78.49	78.54	78.82	79.16	79.17
7	50	86.60	87.45	87.70	88.04	88.43	88.48	88.53	88.88	89.10	89.16
8	60	94.98	95.46	95.56	95.85	96.10	96.29	97.13	97.50	97.95	98.00
9	80	111.53	112.46	112.67	113.06	113.50	113.79	113.91	114.24	114.76	114.80

Table A.14 Laboratory results of flow over semi-circular weirs with semi-circular crest, weir's thickness T = 1.6 cm, the aperture's radius R = 25 cm and the height of weir's edge P = 25 cm.

No.	R = 0.25 cm				P = 25 cm			T = 1.6 cm			
	Q_i (m^3/hr)	h_1 (mm)	h_2 (mm)	h_3 (mm)	h_4 (mm)	h_5 (mm)	h_6 (mm)	h_7 (mm)	h_8 (mm)	h_9 (mm)	h_{10} (mm)
1	4.10	16.91	17.40	17.65	17.93	18.27	18.51	18.67	18.90	19.33	19.85
2	8.25	28.08	28.56	28.81	29.55	29.94	30.15	30.32	30.84	31.00	31.35
3	16.30	43.12	43.58	43.90	44.29	44.97	45.31	45.39	45.90	46.34	47.00
4	28.10	60.95	61.02	61.89	62.23	62.33	62.60	63.13	63.17	63.25	63.87
5	35	69.50	69.76	69.93	70.05	70.43	70.68	70.96	71.29	71.60	71.67
6	40.20	73.27	74.42	74.97	75.23	75.58	76.29	76.73	76.94	77.05	77.19
7	50	84.76	85.55	85.65	85.74	86.46	86.85	86.91	87.01	87.15	87.34
8	60	94.10	94.66	94.96	95.04	95.23	95.50	95.64	95.80	96.40	96.09
9	80	110.06	110.57	110.96	111.35	111.48	112.15	112.31	112.74	112.85	112.98

Table A.15 Laboratory results of flow over semi-circular weirs with semi-circular crest, weir's thickness T = 2 cm, the aperture's radius R = 25 cm and the height of weir's edge P = 25 cm

No.	R = 25 cm				P = 25 cm			T = 2 cm			
	Q_i (m^3/hr)	h_1 (mm)	h_2 (mm)	h_3 (mm)	h_4 (mm)	h_5 (mm)	h_6 (mm)	h_7 (mm)	h_8 (mm)	h_9 (mm)	h_{10} (mm)
1	4.10	13.40	13.81	13.85	14.53	15.46	15.76	15.90	15.99	16.40	17.38
2	8.25	25.50	25.86	26.35	26.66	26.74	27.00	27.09	27.86	28.10	28.35
3	16.30	40.22	40.85	41.08	41.62	41.90	42.34	42.66	42.75	43.95	44.02
4	28.10	58.15	58.50	59.52	59.67	59.82	59.89	60.12	60.25	60.49	60.90
5	35	66.00	66.06	66.63	66.92	67.09	67.22	67.27	67.88	68.48	69.11
6	40.20	71.87	71.99	72.26	72.72	73.56	73.67	73.71	73.79	73.99	74.49
7	50	82.55	82.71	82.88	83.10	83.37	83.52	83.90	84.44	84.67	84.85
8	60	89.86	90.60	90.73	91.11	91.17	91.84	91.95	92.05	92.20	92.33
9	80	106.86	106.98	107.07	107.21	107.43	107.55	108.13	108.65	109.00	109.16

Table A.16 Laboratory results of flow over semi-circular weirs with semi-circular crest, weir's thickness T = 1.4 cm, the aperture's radius R = 15 cm and the height of weir's edge P = 35 cm

No.	R = 15 cm				P = 35 cm			T = 1.4 cm			
	Q_i (m^3/hr)	h_1 (mm)	h_2 (mm)	h_3 (mm)	h_4 (mm)	h_5 (mm)	h_6 (mm)	h_7 (mm)	h_8 (mm)	h_9 (mm)	h_{10} (mm)
1	4.10	22.01	22.35	22.78	23.10	23.51	23.92	24.05	24.22	24.79	24.96
2	8.25	32.21	32.45	32.93	33.30	33.78	34.19	34.53	35.10	36.65	37.00
3	16.30	51.64	51.97	52.35	52.61	52.89	53.16	53.73	54.27	54.75	55.15
4	28.10	70.25	70.59	70.87	71.11	71.44	72.37	72.76	73.50	74.23	74.59
5	35	80.50	80.89	81.32	81.60	81.81	82.29	82.52	82.75	82.93	83.16
6	40.20	87.66	87.95	88.10	88.43	88.58	89.21	89.49	89.80	90.33	90.98
7	50	98.87	99.19	99.58	99.91	100.31	100.73	101.29	101.79	102.24	102.85
8	60	110.23	110.64	110.90	111.20	111.67	112.15	112.81	113.33	113.75	114.00
9	70	120.79	120.99	121.17	121.63	122.39	122.81	123.47	123.68	123.90	124.05

Table A.17 Laboratory results of flow over semi-circular weirs with semi-circular crest, weir's thickness T = 1.4 cm, the aperture's radius R = 20 cm and the height of weir's edge P = 30 cm

No.	R = 20 cm				P = 30 cm			T = 1.4 cm			
	Q_i (m^3/hr)	h_1 (mm)	h_2 (mm)	h_3 (mm)	h_4 (mm)	h_5 (mm)	h_6 (mm)	h_7 (mm)	h_8 (mm)	h_9 (mm)	h_{10} (mm)
1	4.10	20.11	20.48	20.83	21.00	21.27	21.92	22.18	22.65	22.96	23.35
2	8.25	29.98	30.25	30.76	31.14	31.37	31.66	32.51	33.10	33.56	33.95
3	16.30	47.93	48.26	48.57	49.09	49.24	49.61	49.93	50.22	50.45	50.71
4	28.10	62.92	63.41	63.80	64.52	65.11	65.63	66.35	66.72	66.97	67.39
5	35	74.15	74.61	74.92	75.18	75.29	75.41	75.79	76.08	76.55	76.94
6	40.20	80.79	81.07	81.44	81.90	82.25	82.64	83.12	83.37	83.69	83.90
7	50	90.00	90.58	91.30	91.77	92.18	92.46	93.22	93.43	93.78	94.16
8	60	101.29	101.54	101.94	102.28	102.89	103.13	103.65	104.20	104.47	104.85
9	80	120.72	120.89	121.09	121.19	121.36	121.73	122.14	122.54	122.70	122.91

Table A.18 Laboratory results of flow over semi-circular weirs with semi-circular crest, weir's thickness T = 1.4 cm, the aperture's radius R = 25 cm and the height of weir's edge P = 25 cm

No.	R = 25 cm				P = 25 cm			T = 1.4 cm			
	Q_i (m^3/hr)	h_1 (mm)	h_2 (mm)	h_3 (mm)	h_4 (mm)	h_5 (mm)	h_6 (mm)	h_7 (mm)	h_8 (mm)	h_9 (mm)	h_{10} (mm)
1	4.10	17.01	17.26	17.55	18.21	18.76	19.09	19.67	20.31	20.93	21.26
2	8.25	29.60	29.84	30.12	30.31	30.74	31.40	31.82	32.19	32.47	32.89
3	16.30	44.79	44.93	45.23	45.64	46.39	47.61	47.96	48.53	48.71	48.88
4	28.10	61.16	61.37	61.75	62.11	62.60	63.57	64.08	64.42	64.90	65.09
5	35	69.82	70.29	70.95	71.33	71.76	72.28	72.45	72.69	73.00	73.30
6	40.20	75.81	75.97	76.20	76.59	77.19	77.70	78.06	78.41	78.63	78.90
7	50	86.33	86.54	86.79	87.18	87.39	87.66	88.15	88.40	88.65	88.81
8	60	94.74	94.88	95.13	95.24	95.36	96.03	96.56	96.73	97.21	97.54
9	80	110.98	111.25	111.67	112.32	112.90	113.11	113.28	113.59	114.05	114.22

Appendix (B)

Table B.1 Laboratory results calculations of flow over semi-circular weirs with semi-circular crest, when (T) = 1.4 cm, (R) = 15 cm and (P) = 35 cm

T (cm)	h_e (mm)	Q (m^3/hr)	$\frac{R}{h_e}$	$\frac{P}{h_e}$	$\frac{T}{h_e}$	$(\frac{Q}{g^{1/2} * h_e^{5/2}})$
1.4	24.96	4.10	6.010	14.022	0.561	3.694
	37.00	8.25	4.054	9.459	0.378	2.779
	55.15	16.30	2.720	6.346	0.254	2.024
	74.59	28.10	2.011	4.692	0.188	1.640
	83.16	35	1.804	4.209	0.168	1.556
	90.98	40.20	1.649	3.847	0.154	1.428
	102.85	50	1.458	3.403	0.136	1.307
	114.00	60	1.316	3.070	0.123	1.213
	124.05	70	1.209	2.821	0.113	1.145

Table B.2 Laboratory results calculations of flow over semi-circular weirs with semi-circular crest, when T = 1.4 cm, R = 20 cm and P = 30 cm

T (cm)	h_e (mm)	Q (m^3/hr)	$\frac{R}{h_e}$	$\frac{P}{h_e}$	$\frac{T}{h_e}$	$(\frac{Q}{g^{1/2} * h_e{}^{5/2}})$
1.4	23.35	4.10	8.565	12.848	0.600	4.364
	33.95	8.25	5.891	8.837	0.412	3.445
	50.71	16.30	3.944	5.916	0.276	2.496
	67.39	28.10	2.968	4.452	0.208	2.114
	76.94	35	2.599	3.899	0.182	1.890
	83.90	40.20	2.384	3.576	0.167	1.749
	94.16	50	2.124	3.186	0.149	1.630
	104.85	60	1.907	2.861	0.134	1.495
	122.91	80	1.627	2.441	0.114	1.340

Table B.3 Laboratory results calculations of flow over semi-circular weirs with semi-circular crest, when T = 1.4 cm, R = 25 cm and P = 25 cm

T (cm)	h_e (mm)	Q (m^3/hr)	$\frac{R}{h_e}$	$\frac{P}{h_e}$	$\frac{T}{h_e}$	$(\frac{Q}{g^{1/2} * h_e{}^{5/2}})$
1.4	21.26	4.10	11.759	11.759	0.659	5.517
	32.89	8.25	7.601	7.601	0.426	3.730
	48.88	16.30	5.115	5.115	0.286	2.737
	65.09	28.10	3.841	3.841	0.215	2.306
	73.30	35	3.411	3.411	0.191	2.134
	78.90	40.20	3.169	3.169	0.177	2.039
	88.81	50	2.815	2.815	0.158	1.887
	97.54	60	2.563	2.563	0.144	1.791
	114.22	80	2.189	2.189	0.123	1.609