COMPARISON OF TWO MODELS FOR TRANSIENT FLOW OF LIQUIDS IN PIPELINES

A. A. Alamyane[a], M. E. Mashena[b], and I. A. Tuwegiar[c]

[a] B. and C. M. R. Center, Tripoli – Libya,
[b] Mechanical and Industrial Engineering Department,
Al-Fateh University, Tripoli - Libya,
[c] Tajura Nuclear Research Center, Tripoli – Libya.

الملخص

شهدت الثلاثينيات من القرن الماضي بداية العمل البحثي الفعلي في مجال ظاهرة فصل عمود السائل المتدفق داخل الأنابيب، حيث تركزت المحاولات الأولي على البحث التجريبي في محاولة البحث عن طريقة ناجعة لنمذجة وتحليل الظاهرة رياضياً. ومع نهاية ستينيات القرن، برز للإستخدام نموذج عددي عرف بنموذج فجوة البخار المتفرد، والذي ما زال شائع الإستخدام إلى الوقت الحاضر. وقد أصبح هذا النموذج المرجع لكافة الأعمال التي لحقته، والتي بدورها ساهمت في تطويره وإدخال بعض التحسينات عليه.

تقدم هذه الورقة مقارنة تفصيلية بين أداء أسلوبين إعتمدا على نموذج فجوة البخار المتفرد لتحليل ظاهرة فصل عمود السائل، هما: أسلوب ستريتر (1969) وأسلوب كارمونا (1988). وقد إستخدم في المقارنة نفس منظومة الأنابيب التي عالجها كارمونا ولعدد من شروط الإستقرار. بينت نتائج المقارنة بأنّ الحلول بإستخدام أسلوب كارمونا للظاهرة كانت أكثر توافقاً مع النتائج التجريبية.

ABSTRACT

The work on the solution of liquid column separation in pipelines started as early as the 1930's of the last century. Early efforts were based on the investigations of the experimental works in search for a robust method to model and simulate the phenomena mathematically. In the late 1960's, a numerical model known as discrete vapor cavity model emerged, which is still in exclusive use up to the present time. The model became the main reference for most of subsequent works, which in turn contributed to the development and improvement of the model.

In this paper, a thorough comparison is made between two approaches used to solve problems of column separation phenomenon; the well known Streeter's approach developed in 1969, and Carmona's approach developed in 1988. Both approaches are based on the vapor cavity model. The setup analyzed by Carmona is selected for the purpose of comparison, with different steady state conditions, by applying both approaches to the same pipeline system. The obtained results showed that the solution of the cavity as an adiabatic process suggested by Carmona, give better agreement with experimental data, than the famous Streeter's approach.

KEYWORDS: Transient Flow; Column Separation; Discrete Cavity Model; Vapor Cavity; Joukovsky's Head.

INTRODUCTION

The propagation of pressure transients is a normal event in any fluid carrying network; it constitutes the variation of pressure and velocity periodically at any particular point in the network. One of the major concerns for the designers of pipeline systems carrying any fluid is the determination of the maximum, as well as the minimum, pressures in the line during transients.

The problem is even made more difficult when the unsteady local pressure at any point in the pipeline fall to the vapor pressure, causing vapor pockets to form and combine into bigger pockets until it completely fills up the pipe cross-section. When a complete filled up pocket is formed, the fluid column breaks into two portions, upstream and downstream of the cavity, a phenomena so called column separation, [1].

Few numerical approaches for modeling the column separation phenomena are presented in the literature. The forerunner and most exclusive of such approaches is the discrete vapor cavity model that was developed by Streeter in the late 1960's, [2]. The ease of application and simplicity of this model continues to make its use very attractive. Following the introduction of the vapor cavity model, several other studies were performed aiming to well understand the behavior of the liquid vapor mixture flow in pipelines, however, none of the available approaches could provide the optimum solution to the phenomena, thus leaving the door widely open for further investigations.

MODELING OF COLUMN SEPARATION

The formation of intermediate cavities was first recognized by Lopton (1953), and then further investigated by other researchers including O'Neill (1959) and Sharp (1960), [3]. In 1966, Yoshihara Satomi [4] applied the method of characteristics to the solution of column separation phenomena, and tested the two main transient flow models, the vapor cavity model and the air release model. He noted that neither model can provide a complete prediction of the physical behavior of both liquid and vapor during column separation.

In 1970, Tanahashi and Kasahara obtained a mathematical formula to compute the volume change of the vapor cavity at the computational section in terms of the difference in discharge at the upstream and downstream of the section. An alternative approach was also developed in the 1970's that modeled separately the regions in the pipe with different characteristics. These regions included waterhammer region, distributed vaporous cavitation region and localized vapor cavities region. The formation of intermediate vapor cavities in the pipeline was not taken into consideration, [3].

In 1978, Streeter [2] analyzed the phenomena of column separation by using both, the descrete vapor cavity model and the air release model, and applied both models to a real pipeline system in order to prove that the computed results are in agreement with the experimental ones. Other investigators such as; Kranenburg (1974), Provoost (1976), and Streeter (1983) simulated numerically the distributed vaporous cavitation in pipelines, [3]. Internal local column separation was assumed to occur only at the boundaries, high points, or knee, while the possibility of the formation of intermediate cavities was not considered.

In 1986, a Combined Cavity-Distribution Cavitation model was developed by Simpson, by which each of the three flow regimes is treated separately. The major extension incorporated in this model is the inclusion of the intermediate vapor cavities into the analysis, [3]. In 1988 Carmona et al [5] developed a new procedure to evaluate liquid column separation phenomena based on dividing the solution into three steps, with respect to the pressure wave travelling between both pipeline ends. Each step begins at the downstream end and terminates at the same point after the pressure wave travels along the pipe length twice. The procedure was based on the method of characteristics with a minor adjustment for the analysis of column separation.

Carmona concluded that it is possible to generalize the method of characteristic by introducing some modifications to evaluate the pressure head up to the third step. For transient pressure surge, Carmona found that during the first three steps, the results evaluated using the proposed method are in good agreement with the measurements performed in the laboratory, both in magnitude and time.

Other investigators cited recent experiences with modeling the phenomena of column separation, among them Martin, Padmanabhan and Wiggert [6], Ewing [7], and Marsden and Fox [8]. Most of such studies focused on how to model the vapor cavity numerically, in addition to the mechanism of air and water vapor release and absorption. In an effort to compare the performance of the pioneer approach of Streeter with that of Carmona, Alamyane [1] conducted a detailed analysis to the results of both approaches for the solution of the column separation.

THE DISCRETE VAPOR CAVITY MODEL

The most commonly used model for column separation analysis at the present time is the discrete vapor cavity model. The first development of this model was done by Streeter (1969), and independently by Tanahashi and Kasahara (1969), [3]. In this model, the cavity is assumed to be able to form at any of the computational sections, and therefore is confined to the same sections. The model also assumes a constant wave speed.

The computational scheme depends on examining if the computed section pressure to check equals to, or below, the vapor pressure. If it is the case, the pressure is held at the vapor pressure, and the section is treated as a fixed internal boundary conditions since the situation is not a general waterhammer case. This means that the cavity is generated, grown, and then collapsed in accordance with the conservation of mass principles at the section. The vapor cavity model assumes that the vaporous cavities are limited to the computed sections when vapor pressure is reached.

The main objective of the vapor cavity model is to compute the size of the bubble during the existence of the cavity (balance between the average of volume flow rate entering into and exiting from the section) by using of the characteristics equation during the time step. For more details on this model, the reader may refer to the Fluid Transient book witten by Streeter and Wylie (1978) [2].

STREETER's APPROACH

The vapor cavity model, which is used to solve problems of column separation, was developed based on the following assumptions:

- The cavity may form at any computed section.
- The formed cavity is concentrated at the computing sections.
- Constant wave speed.

The model utilized the method of characteristics to integrate the governing partial differential equations, it is applied to the entire pipeline including the cavities that are at the vapor pressure head of the liquid.

CARMONA's APPROACH

This approach was formulated in accordance to the experimental events generated as a result of rapid valve closure at the downstream end of the pipeline. The approach was based on the following assumptions:

- Only one very small bubble is developed, so that it is possible to consider a constant liquid column length.
- Water vapor pressure is the minimum value that the transient pressure can reach at any section within the pipeline.
- The collapse of the gas bubble is idealized by the adiabatic compression of an ideal gas relationship $PV^n = K$. This means that the gas condensation is very slow and can be neglected.
- If water column separation is caused by air inclusion through a vacuum-breaker valve, the minimum pressure is equal to the atmospheric pressure at the section where the valve is located.

COMPARISON OF THE TWO APPROACHES

In order to compare the two approaches in solving the column separation problems, the same case study presented by Carmona is selected herein to be the base for the comparison. The case study constitutes of two control pressure tanks connected together by a simple horizontal pipe 1460 m long, and 104 mm in diameter. A rapid valve closure mechanism is installed near the downstream end to generate pressure transients. Schamatic drawing of the system is shown on Figure (1).

Figure 1: Horizontal pipe with downstream valve (Carmona's setup)

The initial flow velocity and the static head of the upstream tank are 0.774 m/s and 70 m respectively. The Joukovsky number $\left(hr = aV_0/gH_0\right)$ is used as a characteristic number and the solution is obtained for *hr* = 1.3, 1.58, and 2, Where:

a : the pressre wave velocity.
V_0: initial flow velocity.
H_0: static head of the upstream tank.
g: acceleration due to gravity.

Three different conditions of flow were eximined on the given case study, with the transient source being the closure of the downstream valve. Figure (2) compares the pressure versus time trace obtained from both approaches at the valve (downstream end) and pipe midpoint for the system shown in Figure (1).

The solution obtained by each of the two approaches will be described according to the events that take place in the pipeline. These events are divided into three steps that are stirred as a result of valve closure at the down stream end. Each step starts and ends at the downstream end (valve section) after traveling twice across the pipe length and contains positive and negative waves.

The duration of the first step extends between the start of valve closure and the time of the arrival of the first negative wave to the valve section. At the downstream end of the pipe (the valve section), and as a result of the rapid valve closure, the fluid stops moving and condensate upstream the valve, thus causing a pressure rise up to a value called Joukovsky's head, the value of which depends on the initial condition of the tested system. The fast condensation of the fluid at the valve upstream will generate a reversible movement known as pressure wave that travels from the down stream end of the pipe (the valve) towards the reservoir at the upstream end (the so called first positive pressure wave), while the head inside the pipe equals to Joukovsky's head. The pressure wave is then reflected at the reservoir and travels back to the valve (the so called negative pressure wave) causing pressure reduction in the up stream of the pipe while the pressure head at the valve is still constant (equals to Joukovsky's head). Finally the wave arrives at the valve after a time of *2L/a* seconds from start of the valve closure.

The value of the pressure at the valve section increases gradually along the first step due to the pipe wall friction while the pressure wave crosses the pipe length twice, which can be seen as an inclined line on the first part (1st step) of Figure (2). It is clearly shown that Streeter's Approach gives higher values of Joukovsky's head than Carmona's Approach in all tested systems.

After ending the first step, the second step starts and continues with a duration that ends when the second positive wave arrives to the valve section. The second step starts when the first negative pressure wave reaches the valve section and reflects back toward the reservoir as a second negative pressure wave causing a pressure drop down to the vapor pressure. This means that the cavity is formed at the downstream end, and grows up until it collapses suddenly at a certain time after valve closure, after which the pressure remains constant at the vapor pressure until the pressure wave crosses the pipe length twice and arrives again at the valve as the second positive pressure wave, thus marking the end of second step.

The formation of the cavity occurred approximately at the same time in all tested systems, while the duration was different and found to be not a multiple of *2L/a* seconds. Duration has longer periods in Streeter's Model results as shown on part 2 (2nd step) on Figure (2).

The third step's duration extends between the reflection of the second positive pressure wave and the arrival of the third negative pressure wave to. When the second positive wave reaches the valve the third step starts and the pressure at the pipe increases until the cavity collapses, thus producing a static head rise depending on the cavity size, duration, and Joukovsky's head. The cavity collapse produces a second water hammer wave in the pipe in addition to the original valve closure wave. When the original valve closure wave arrives back at the valve during the end of the second step, a short duration pressure pulse occurs as a result of the superposition of the initial valve closure wave and the cavity collapse wave.

At the time of valve closure, the pressure at the pipe-mid point still equals to the steady state head, while the fluid condensate towards the valve, until the first positive pressure wave arrives at the pipe-mid point causing pressure rise to the Joukovsky's head. The pressure remains constant at Joukovsky's head until the pressure wave reflects at the reservoir and arrives back to the pipe-mid point as the first negative pressure wave crossing the complete pipe length. The pressure head drops to the steady state value. So the first step acts on the pipe-mid point by both movement in both directions as shown on the first part of Figure (2). The pressure head will be fixed at the same value (steady state) until the pressure wave moves half of the pipe length, where the wave is reflected at the valve (end of the first step and beginning of the second step) and coming back to the pipe-mid point as the second negative wave, thus decreasing the pressure head to the vapor pressure head, then the cavity is formed and grows up until the pressure wave crosses the complete pipe length and is reflected at the reservoir as the second positive pressure wave where the pressure head returns to the original value and remains fixed until the pressure wave moves half of the pipe length and reflects at the valve as the third positive pressure wave (end of the 2nd step and beginning of 3rd step).

When the second positive pressure wave arrives at the valve, the cavity at the valve collapses due to the head rise, consequently, resulting in the pressure drop in the entire pipe while the fluid is still moving toward the valve. This drop can be seen as a negative pressure pulse at the beginning of third step on Figure (2). The first positive pressure pulse, seen on Figure (2), is a result of the collapse of the cavity at the pipe mid-point, and has a value higher than the original pressure value with time delay of about *L/a* seconds. The second positive pressure pulse observed on the Figures is resulted from the cavity collapse at the valve which produces a pressure rise at the pipe mid-point.

When the vapor cavity at the valve collapses immediately following the reflection of the valve closure wave at the downstream end valve, narrow short duration pressure pulses are resulted due to the wave superposition. Whereas, when the cavity collapses just prior to the reflection of the valve closure wave, wider short duration pressure pulses occur. The shorter the time of the existence of the cavity at the valve, the larger the magnitude of the short duration pulse relative to the Joukovsky head rise, [8].

CONCLUSIONS

As shown in Figure (2), the results obtained by Streeter's approach has higher Joukovsky's head than Carmona's, while both approaches indicate that the vapor pressure head occurs at the same time in agreement with experimental results. Further, the period of the cavity duration obtained by Streeter's model is greater than that obtained by Carmona's, however, both are higher than the experimental results. The existence of the cavity is similar in both models, but the period of duration is different, it has longer duration in Streeter's model. The pressure head rise obtained by Streeter due to the pulses resulted from the cavities collapse is higher than that obtained by Carmona with wider duration. The time duration of the three steps is not equal to the multiple of *2L/a* seconds in both models.

Two cavities are formed at the pipe mid-point in Streeter's results which produces anther pressure wave results from the cavities collapse that can be seen as small edges on the HGL, where as only one cavity formed in Carmona's model. The main difference between the two models usually occurring through the third step (after *4L/a* seconds of valve closure). The difference in comparison is due to the modification done by Carmona to predict the experimental recorded data.

The main conclusions of this work are the solution of the cavity as an adiabatic process such as that used by Carmona's model improves the prediction of experimental data, it has improved the solution procedure by specifying the analysis step by step, and identifying all events in details, so the solution must buildup on the analysis of the events that preceding the occurrence of the liquid column separation.

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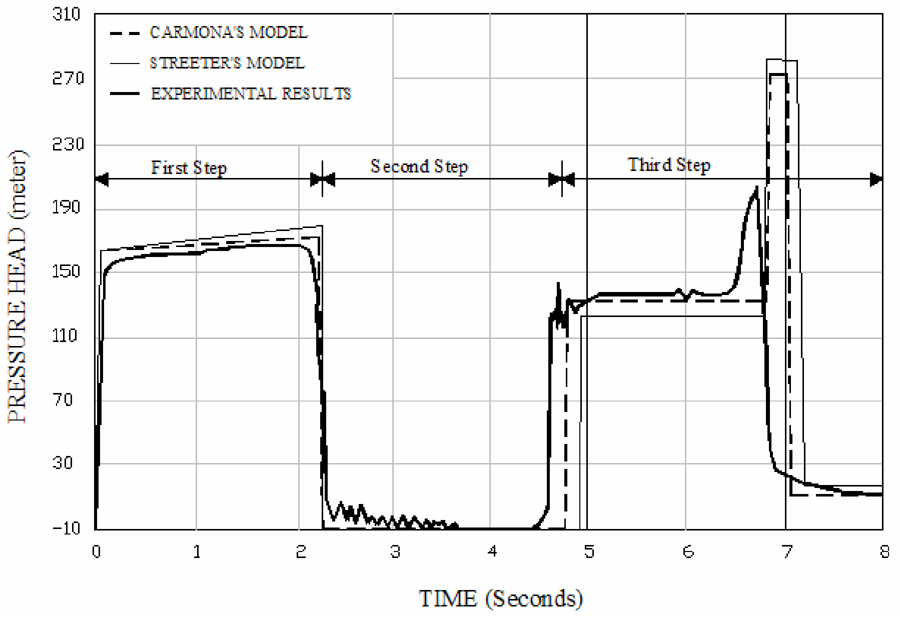
Pressure Head at Pipe Downstream End (Valve Section),
$H_0 = 70$ m, $V_0 = 0.774$, $h_r = 1.3$



Pressure Head at Pipe Midpoint, $H_0 = 70$ m, $V_0 = 0.774$, $h_r = 1.3$

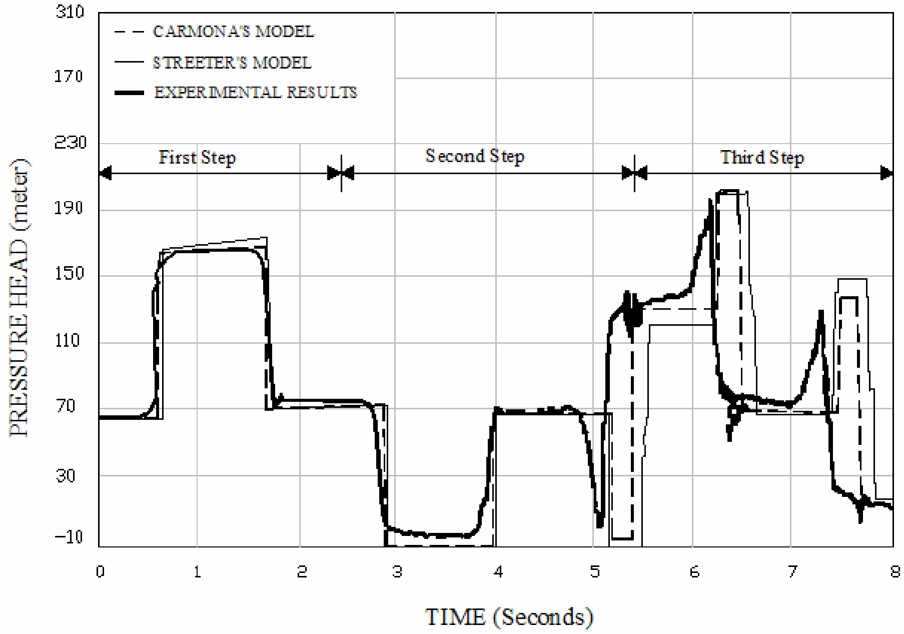
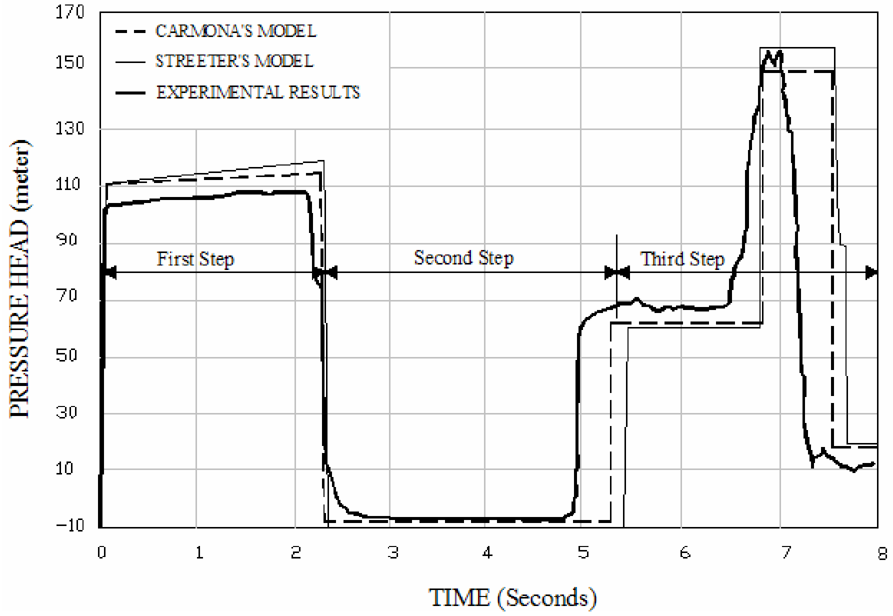


Figure 2: Comparison between pressure heads at Pipe Downstream end and Midpoint obtained by Carmona's and Streeter's approaches with the experimental results.

Pressure Head at Pipe Downstream End (Valve Section),
$H_0 = 39$ m, $V_0 = 0.567$, $h_r = 1.58$



Pressure Head at Pipe Midpoint, $H_0 = 39$ m, $V_0 = 0.567$, $h_r = 1.58$

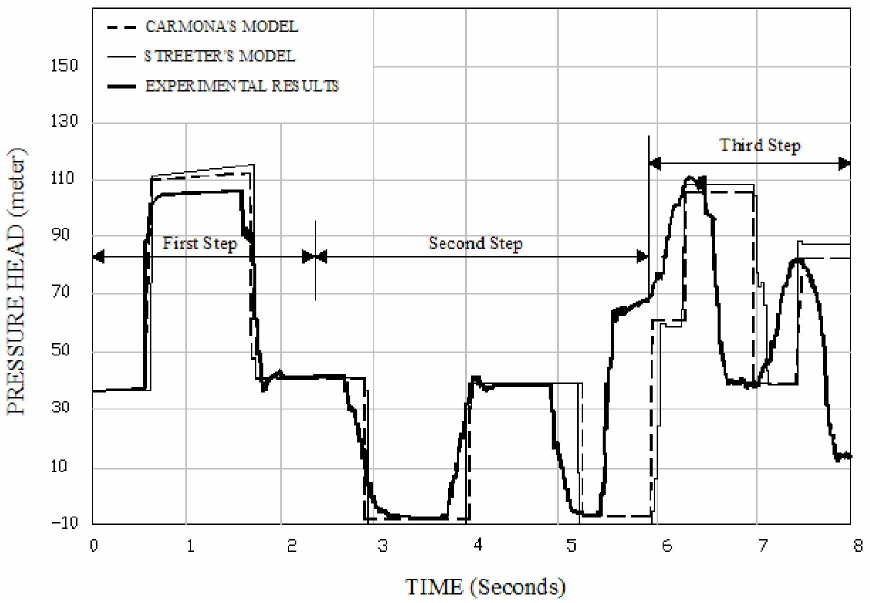
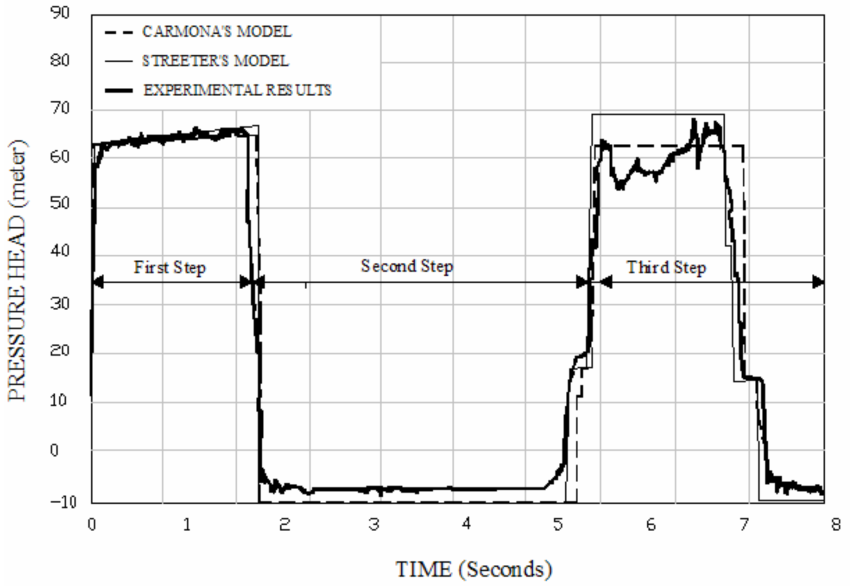


Figure 2 - cont.: Comparison between pressure heads at Pipe Downstream end and Midpoint obtained by Carmona's and Streeter's approaches with the experimental results.

Pressure Head at Pipe Downstream End (Valve Section),
$H_0 = 16$ m, $V_0 = 0.375$, $h_r = 2$



Pressure Head at Pipe Midpoint, $H_0 = 16$ m, $V_0 = 0.375$, $h_r = 2$

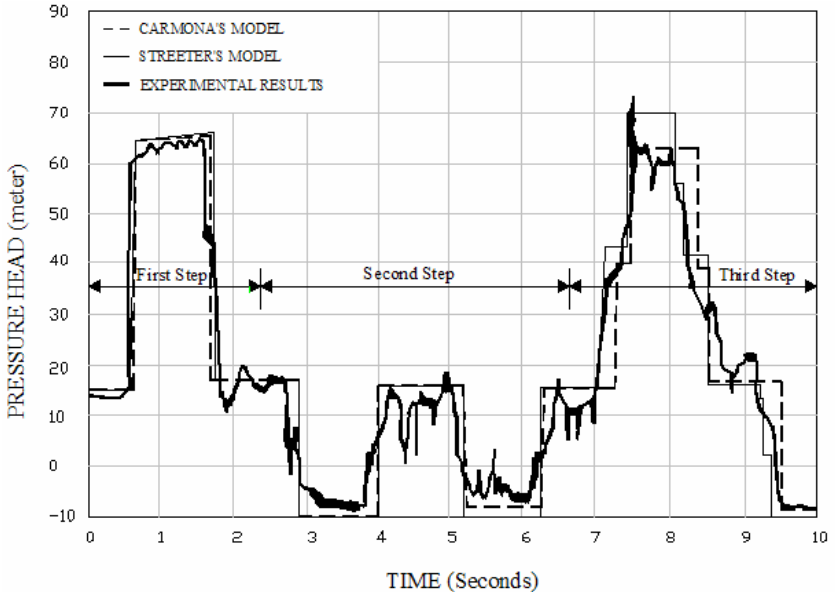


Figure 2 - cont.: Comparison between pressure heads at Pipe Downstream end and Midpoint obtained by Carmona's and Streeter's approaches with the experimental results.