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Transient Studies for a Low and High Pressure Hydraulic Jack System

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Summary

A hydraulic jack system in a shoe factory in Zlin, Czech Republic has been used for pressing half soles thirty years without any incidents. In 1995 one of the pressure vessels suddenly ruptured and exploded. Questions were raised whether the cause of failure was due to unexpected operation and/or poor maintenance. In the past a detailed computer analysis had not been carried out, only several simplified calculations which could not cover all possible operating events. No commissioning tests had been undertaken.

The purpose of this paper is to describe a computer investigation of the existing system to evaluate its hydraulic behaviour and identify possible causes of the incident. A computer analysis of the proposed new pressure vessel has assessed the safety of the overall system with respect to transient flow events. The simulations included the trip and start-up of the pumps and the rapid closure of the emergency box valves. Unfortunately, these transient analyses have been performed after the incident where one man was killed. A set of site tests is planned to obtain data for the system validation.

1. INTRODUCTION

Computer codes for a computer-aided analysis of hydraulic transients in pipe networks are nowadays used to early out preliminary and/or detailed studies. Even during the construction phase of the project and the commissioning tests the computer analyses should be carried out. This enables the designer and operator to ensure that the system will operate satisfactorily under normal and emergency operating conditions.

In this particular case analyses were carried out late, after an event which has led to a casualty. The authors were trying to determine the cause of failure and suggest some improvement. The original design drawings and some of the component data were not complete Inspection after the incident revealed that the steel pressure vessel suffered corrosion and over a period of time the wall thickness had eroded. In addition to this problem, the pressure vessels were equipped with pressure relief (safety) valves but not on the delivery side of the compressor. Hence the compressor could have produced an excessive air pressure.

2. SYSTEM DESCRIPTION

A schematic layout of the hydraulic jack system is presented in Fig. I. It consists basically of two pressure systems, namely a low pressure piping system (LPS) and a high pressure piping system (UPS). Both systems are located at two levels. In the first level there are pumps and pressure vessels, in the second level there are hydraulic jacks. The low pressure system feeds the water into the hydraulic jack chambers at a pressure of about 4 MPa. The flow rate is supplied by three positive displacement piston pumps in parallel. Each triplex pump operates at 310 rpm and delivers 0,00 16 m at a maximum pressure of 4,8 MPa. The water is drawn from a supply vertical cylindrical tank of height 4 m having a diameter of 1,9 m. It is located close to the pumps (not shown in Fig. 1). Three pumps run simultaneously, one pump is kept on standby. The filling of the hydraulic jacks is carried out with the help of 6 pressure vessels and it takes about 15 or 20 seconds. The pressure vessels both supply the hydraulic jack system with water and protect it from hydraulic transients. Each pressure vessel is of 250 L volume (0,28 m in diameter, 4 m high, 9,5 mm wall thickness), Fig. 2. There is a pressure relief valve at pump discharge and a check valve in the connecting lines. This check valve can be used as isolation valve audit also prevents the system from air entering. The inflow into the hydraulic jacks is stopped by a box valve, Fig. 3. The piping in the low pressure system is 89 mm in diameter and 5 mm thick, operates at a pressure of 4,0 MPa and its total length is 550 m.

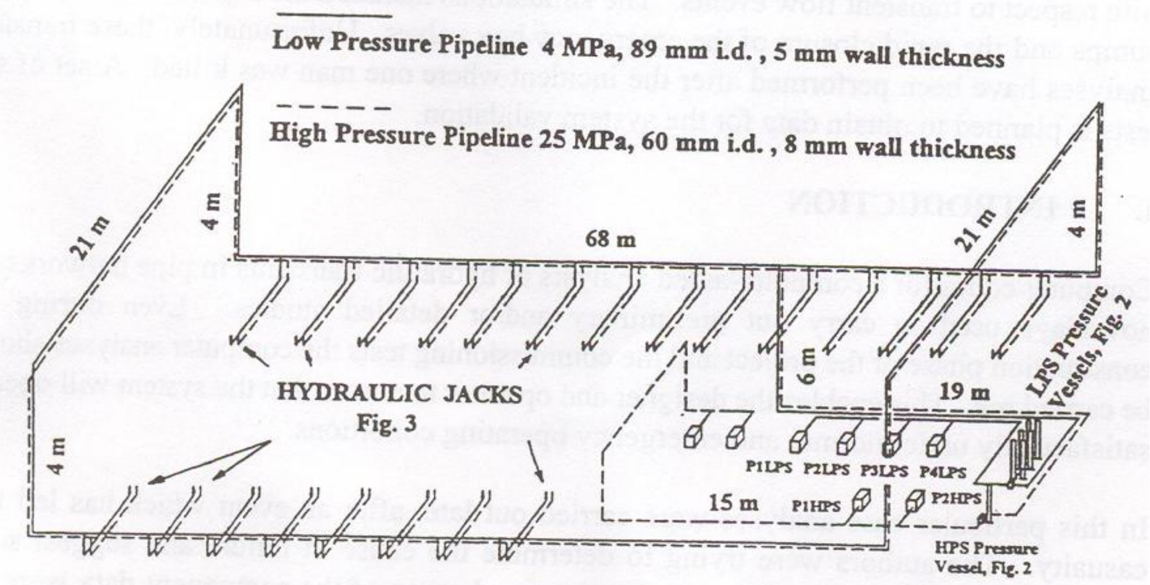

Fig. 1 Schematic layout of a hydraulic jack system.

There are two triplex piston pumps in parallel for the high pressure system. Each triplex pump operates at 310 rpm, delivers 0 m at a pressure of 25 MPa and there is a pressure relief valve in the pump discharge line. There is only one pressure vessel (0,28 m in diameter, 4 m high, 38mm wall thickness), Fig. 2, with a check valve in the connecting line. The steel piping in the high pressure system is 60 mm in diameter, 8 rum thick, withstands the pressure of 25 MPa and its total length is 515 m. At the location of hydraulic jacks, Fig. 3, both systems are separated by a special box valve which is here represented by a control valve CV1. This simplification had to be accepted because the box valve characteristics were not known. After the incident they installed on the HPS piping the control valve CV2 in order to separate the hydraulic jack itself from the rest of the system and to increase the system safety.

After filling time (15 -20 s) the box valve closes and separates the LPS from the hydraulic jack. Then the box valve opens and connects the HPS with the hydraulic jack. The maximum number of hydraulic jacks which can operate at a time is 4. The operation time for a press curing is about 15 minutes during which the HPS pump must maintain a high pressure of about 25 MPa. Then the water is drained away into the water supply tank, which is common for both systems, and the working cycle of the whole hydraulic jack system can be repeated.

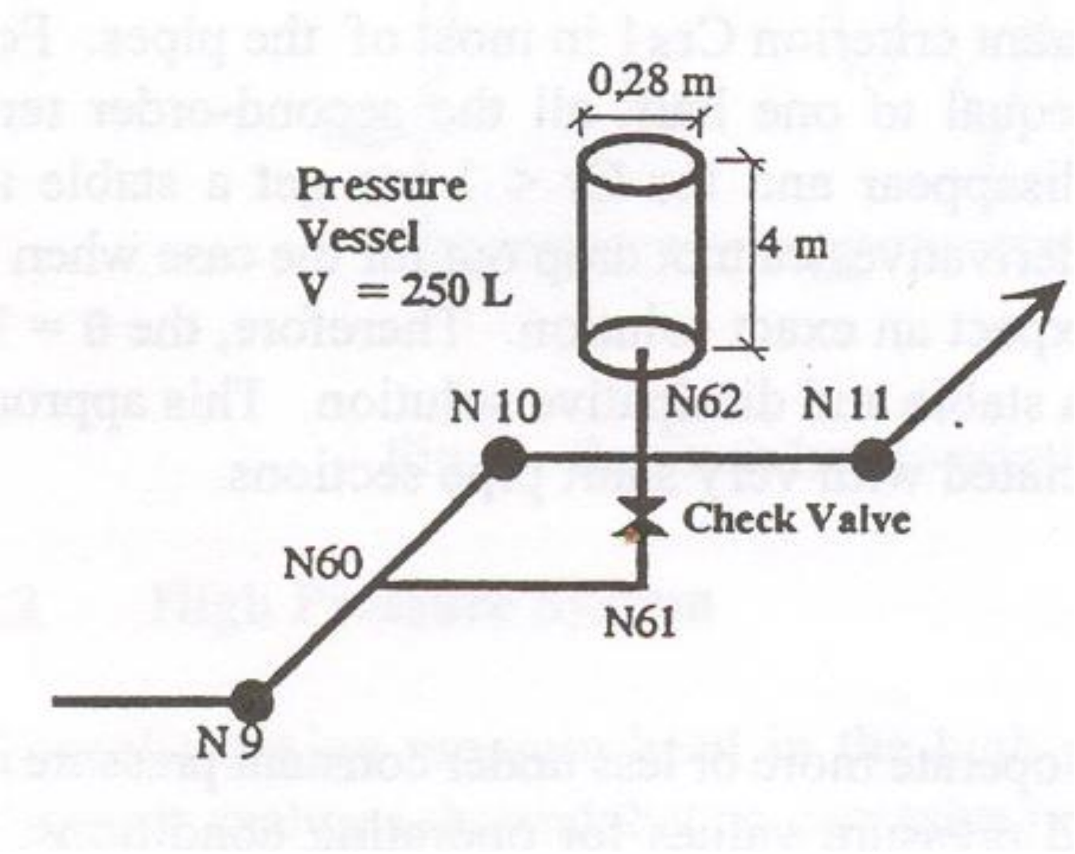

Fig. 2 Pressure vessel of the hydraulic jack system.

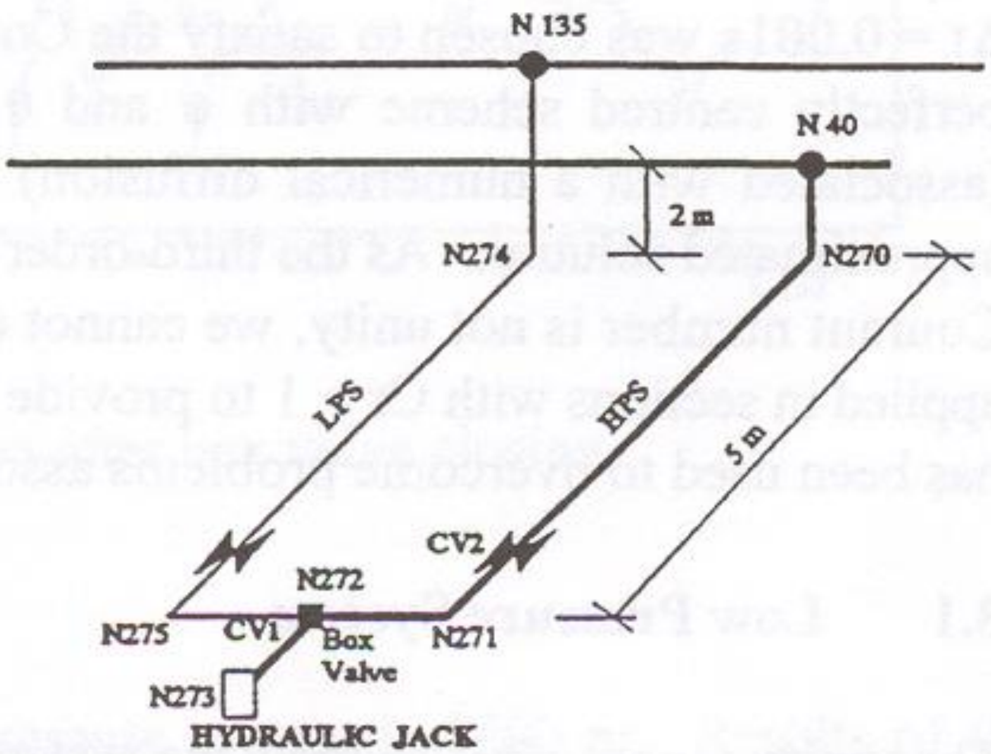

Fig. 3 Schematic layout of the hydraulic jack.

3. COMPUTER ANALYSIS

A software package HYPRESS was used in this study for water hammer analysis. The program was developed to solve the one-dimensional steady and unsteady flow equations in closed-conduits. The governing equations, Chaudhry (1987), are solved by the most advanced fourth-order-accurate, space-compact implicit finite difference scheme, Verwey and Yu (1993). The scheme was developed by adding two Preissmann type operators over two successive time levels and by subtracting all third-order derivative terms of the truncation error.

An object oriented design, Ingeduld et al (1994), can provide a flexible description of a variety of pipes and hydraulic components such as pumps, valves, reservoirs, surge chambers, feeder tanks and air vessels. A modular structure of the computer program is based on graphical facilities for the definition and checking input data It provides an accurate and fast numerical solver and an engineering approach to presenting output data A package structure may benefit from a database platform enabling query-by-example and other modem data handling facilities.

A preliminary computer analysis of the accident has been undertaken which predicted that due to a malfunction of the box valve, the low pressure system could operate outside its design limit The investigations of the hydraulic transients simulated the trip and start-up of the pumps and the closure time of the box valve. The sensitivity of various parameters has been assessed, e.g. the capacity and a number of the pressure vessels in the low pressure system, the valve closure time, simultaneous operation of several hydraulic jacks etc. The wave speed has been calculated for both systems and the values varied from 1340 ms to 1390 ms’. Since there are a lot of short pipelines in the system, a small time step of At = 0,00ls was chosen to satisfy the Courant criterion Cr = l in most of the pipes. For a perfectly centred scheme with θ and ψ equal to one half, all the second-order terms (associated with a numerical diffusion) disappear and for Cr < 1 we get a stable and approximated solution. As the third-order derivatives cannot drop out for the case when the Courant number is not unity, we cannot expect an exact solution. Therefore, the 6 = 1 is applied in sections with Cr > 1 to provide a stable and dissipative solution. This approach has been used to overcome problems associated with very short pipe sections.

3.1 Low Pressure System

The triplex pumps which supply the system operate more or less under constant pressure and flow rates. Therefore, based on measured pressure values for operating conditions, the triplex pumps were represented by H - boundary conditions with a pressure of 408 m and 2550 m respectively. The transient pressures in the low pressure system may be caused by several events. During the pump start-up the filling flow rate increases up to Q = 0,00316 m^3/s. The maximum closing time of the box valve was t = 0,5s. Multiplate hydraulic jacks which are connected with LPS and HPS systems via the box valves were modelled as a Q - boundary condition. The simultaneous operation of 4 hydraulic jacks was considered based on the factory operation experience. If six pressure vessels were connected to the system and a delivered flow rate was 0 = 0,003 16 m^3/s the change of the pressure head between nodes N274 and N275 (see Fig. 3), after the box valve was closed within 0,5 s is shown in Fig. 4. The value of the pressure head increased from the normal operation conditions which is 408m to the maximum value of about Ha = 455 m. Providing that six pressure vessels are connected to the system, the pump starts-up at a pressure head 390 m and the box valve closes within 0,5 s, the time change of the pressure head is illustrated in Fig. 5. The maximum value of the pressure head achieved was H = 463 m. Also for this case, the system pressure head is still below its designed limit which is about 520 m. Under normal operating conditions simulations did not show any risk of a failure.

The authors recommended to modify the LPS and to replace 6 pressure vessels by only one which has the same volume. One pressure vessel was designed as a vertical cylindrical tank of height 2 m having a diameter of I m. Again, simulations of normal operating conditions proved that the LPS worked reliably. This modification has been accepted for a final reconstruction.

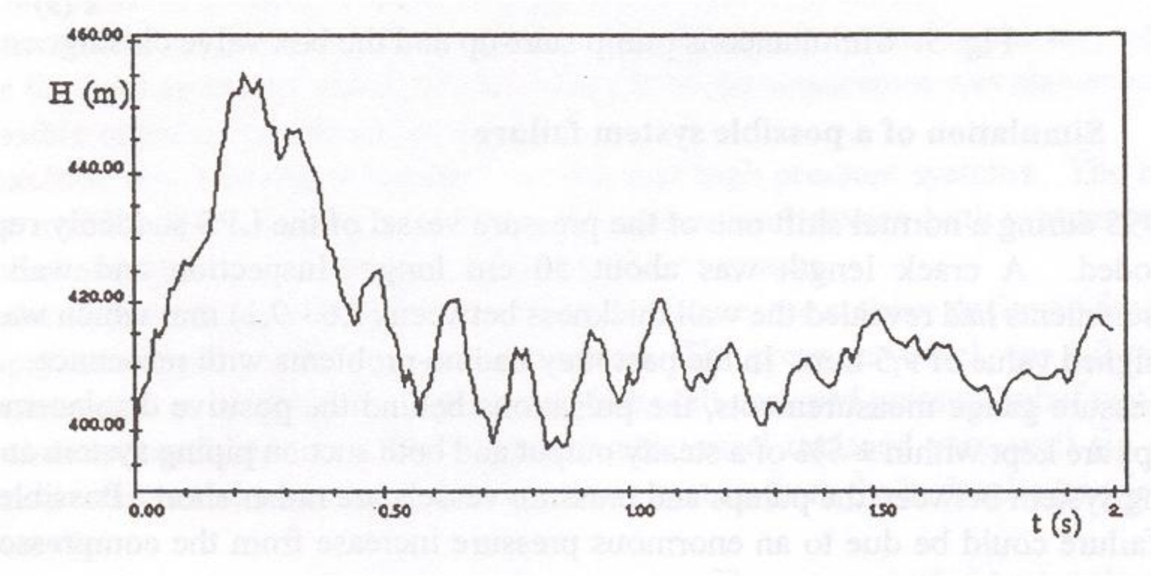

Fig. 4 Pressure head variation after box valve closing.

3.2 High Pressure System

Normal working pressure head in the high pressure system is 2500 m. Results of the computer analyses showed that no excessive pressures would occur under normal conditions when for example the pump starts-up and/or the working cycle finishes, water is drained away and the pressure drops down to value 400 m which corresponds with the low pressure system. Moreover, the hydraulic jacks are also protected by pressure relief valves.

Since they had decided to place additional control valves CV2 (see Fig. 3), we had to evaluate this modification. Simulations revealed a potential danger of excessive pressures on both sides of the control valve. If this valve closed simultaneously with the box valve, the pressure head could increase up to 2700 m. Therefore we recommend using the CV2 very carefully only as isolation valve and not as control valve.

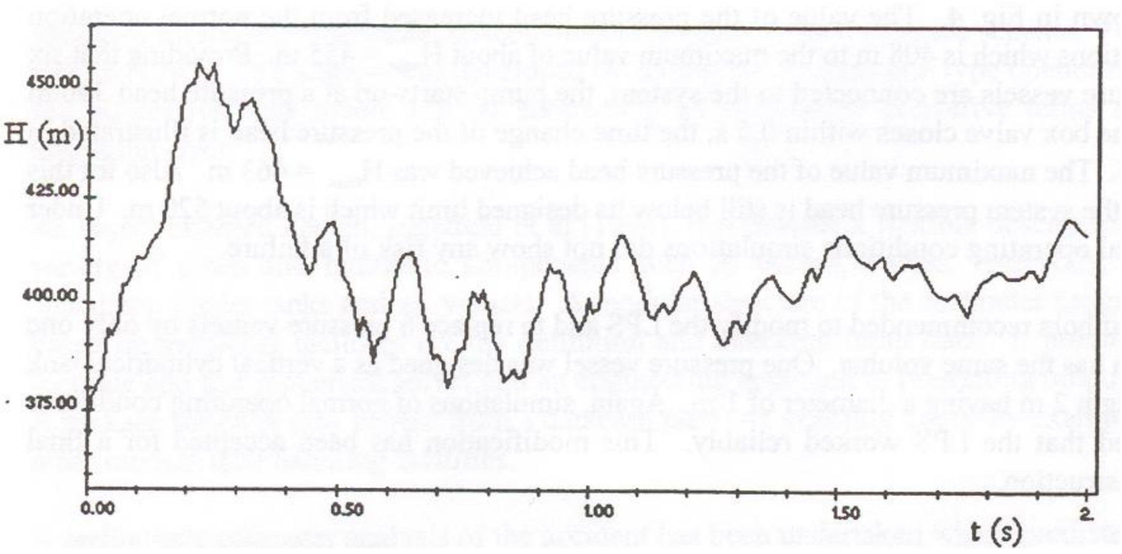

Fig. 5. Simultaneous pump start-up and the box valve closing.

3.3 Simulation of a possible system failure

In 1995 during a normal shift one of the pressure vessels of the L suddenly ruptured and exploded. A crack length was about 50 cm long. Inspection and wall thickness measurements had revealed the wall thickness between (7,6 - 9,1) mm which was less than a designed value of 9,5 mm. In the past they had no problems with resonance. According to pressure gauge measurements, the pulsations behind the positive displacement triplex pumps are kept within ± 5% of a steady output and both suction piping system and delivery piping system between the pumps and pressure vessels are rather short. Possible causes of the failure could be due to an enormous pressure increase from the compressor and/or a malfunction of the box valve.

The pressure vessels of both LPS and HPS are connected to the same compressor which may produce a pressure up to 10 MPa. Unfortunately, there was not any pressure relief (safety) valve on the delivery side of the compressor. Simulations showed that uncontrolled increase of the pressure from the compressor to about 8 MPa could have caused the crash of the pressure vessel. The overpressure setting of 5,5 MPa was sufficient to protect the LPS pressure vessels.

Both pressure systems are separated via the special box valve, Fig. 3. The authors also simulated the abnormal extreme event, when the box valve malfunction could cause the hydraulic connection between both systems. The pressure head in LPS was $H = 408$ m and the filling flow rate into hydraulic jacks was stopped by the box valve within 0,5 s. The pressure head in HPS was $H = 2550$ m and both systems became interconnected. Simulations showed that the maximum pressure increase in LPS would be 2 times more than under normal operating conditions, Fig. 6, which could destroy the low pressure system.

4. CONCLUSIONS

Final checking of any design should generally be carried out with the aid of a computer-aided analysis and commissioning test program. Unfortunately it has not been done for the hydraulic jack system shown in this study. Computer-aided analyses have been undertaken after the incident when one pressure vessel of the low pressure system ruptured and one man was killed.

Simulations tried to identify possible causes of the failure incident. From the investigations the following conclusions can be drawn:

- The need to analyse such system using a suitable computer program
- The need to maintain systems and to control all system components, in particular pressure vessels, pressure relief valves and the special box valves
- The need to design inherently safe systems. The absence of a suitable pressure relief valve for the compressed air on the delivery side of the compressor was shown to be a possible cause of the failure incident

- To exclude any interaction between the low and high pressure systems. The box valve malfunction could cause a hydraulic connection between both systems and unacceptable pressure increase in the low pressure system
- In order to prevent repetition of the event in the future, the authors designed for the low pressure system only one pressure vessel. The pressure vessel was 1,0 m in diameter and 2 m height and it is equipped with well designed pressure relief valves. Simulations confirmed that this large pressure vessel replaced very well six old pressure vessels and protected the low pressure system from the hydraulic transients very well
- The commissioning tests are very important. They are needed not only for verification of the mathematical model but they could also discover the absence and/or the importance of the pressure relief valves.

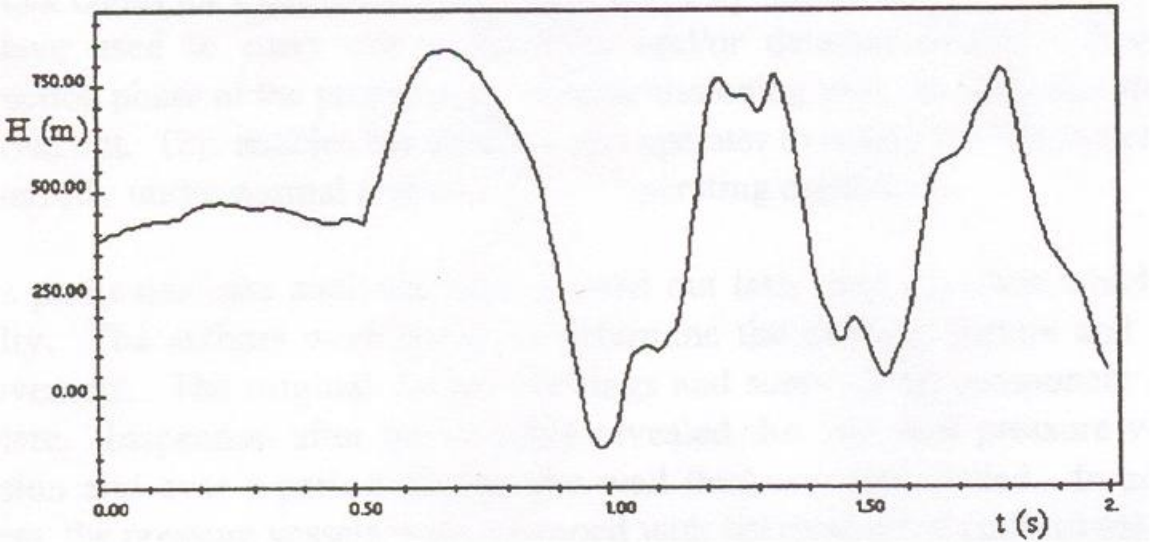

Fig. 6 Pressure head increase in the low pressure system during interconnection of both systems

5. ACKNOWLEDGEMENTS

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