Measurement of entrapment hazards caused by drainage systems in swimming pools

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Abstract
During the last few years dozens of severe and fatal entrapment accidents have been reported in swimming pools. Statistical analysis has shown that the majority of these accidents are related to the entrapment by suction of body and limbs on submerged drainage intakes. The case of a 12 year old boy is described, who did not drown, but was killed by the exposure to a large negative gauge pressure. Scientific studies and experimental research have shown that large negative gauge pressures can occur in various layouts of water circulation systems. How much negative gauge pressure is built up behind a blocked drainage intake can be approximated with models, but modeling entrapment is not always feasible in existing swimming pools. A method is described with which the negative gauge pressure can be measured during a simulation of suction entrapment. The actual suction forces of drainage intakes can now be determined in existing pools and allows the risks of suction entrapment to be detected before accidents occur. In addition, the measurement of the negative gauge pressure allows the effective operation of safety measures to be tested in each specific new or existing situation.

Keywords
Measurement; suction entrapment; hair entrapment; pool safety; suction force; negative gauge pressure

INTRODUCTION

In swimming pools water is circulated for quality control and to feed water slides and other water attractions. Water is generally removed from the swimming pool by means of an overflow gutter or by suction through a drainage system in the pool’s floor or walls. Suction through drainage systems is known to cause an increased hazard potential for swimmers. Swimmers that block the intake of a drainage system can be exposed to a negative gauge pressure. The suction force with which swimmers are held against the drainage intake can be of such magnitude that they are no longer able to free themselves and drowning or serious internal injuries may occur. In addition, the entrapment of long hair and small limbs on the grille covering a drainage intake are common causes of entrapment accidents.

Pool entrapment accidents

Annually, dozens of pool entrapment accidents occur in swimming pools worldwide. Recent studies have shown that 206 accidents have been reported worldwide in the last 10 years (Gipson, 2012, 2013; Hnatov, 2014; Avezaat & Göb, submitted), in which 77 swimmers were killed and 122 swimmers were injured. Of these accidents, 150 cases were related to entrapment by suction of body and limbs and 29 cases were related to the entrapment of hair. Almost all reported victims were children aged 2 to 16 years.

Injuries

Entrapment by suction or the entanglement of hair on the grate covering a drainage intake can lead to drowning of the trapped victim. Locks of hair and even parts of the scalp sometimes need to be removed to free someone from a hair entrapment accident. The exposure to a large negative gauge pressure in a suction entrapment accident can cause severe injuries. Large negative gauge pressures can cause haemorrhages and even disembowelment (Juern et al., 2010). One specific case shows the devastating force a drainage intake can have. A 12-year-old boy was killed in a suction entrapment accident after blocking a drainage intake in the whirlpool area of a hotelpool. Autopsy on the boy revealed a blue haemorrhage on the lower abdomen in the shape of the grate that covered the intake (Cutrignelli, 2010). The immense suction force that is able to cause such a wound was estimated to be at least 2 kilonewton. The effusion of blood into the visceral nerves led to a failure in the blood flow towards the heart, brain and lungs and the mechanical activity of the diaphragm was hindered by the pressure exerted on the lower abdomen. The boy lost his consciousness within seconds after making contact with the intake. The pathologist concludes that the boy was killed by acute heart failure and rupture of the aorta before drowning occurred, as water was mainly found in the upper respiratory tract. After the boy's death, his grandfather started The Blue Cap Foundation in the Netherlands, which strives for technical safety of swimming pools.

MODELING ENTRAPMENT RISK

An academic study of the Blue Cap Foundation in cooperation with the University of Twente has shown that suction entrapment in both new and existing pools can be assessed using analytical or computational models (Avezaat, 2013). The flow of water through pipes and other components of a water circulation system is established by applying a differential pressure over that circulation system. A pressure drop occurs in such systems as the flow of water is subjected to frictional effects (Çengel & Cimbala, 2010; Pritchard et al., 2011). This pressure drop can be divided into major pressure losses in pipes and minor pressure losses in pipe entrances, exits, fittings, bends, branches, expansions and contractions of the pipe. In swimming pools, pressure losses also occur in components of the filtration system. Pressure loss in a circulation system can be approximated with pressure loss equations (Çengel & Cimbala, 2010). The pressure loss in a pipe system can increase significantly with higher flow velocities, smaller pipe diameters and large pipe distances. Pumps are used to increase the pressure in a circulation system to overcome all the pressure losses that occur at a desired volumetric flow rate. How a negative pressure can build up behind a blocked intake due the pressure loss in another section of the system is shown in figure 1.

Analytical modeling or Computational Fluid Dynamics can be used to approximate the pressure loss in a water circulation system at a chosen or desired flow rate. The local pressure behind a blocked grate of a drainage intake can be approximated with such models to determine whether swimmers blocking the intake are exposed to a negative gauge pressure. However, some problems arise when modeling existing circulation systems. An accurate predicting of the local pressure somewhere in the circulation system requires the dimensions of all used system components to be known. In existing pools, large parts of the water circulation system are often encased in concrete. Then it is difficult and time-consuming to find out which dimensions were used for the pipes and components, along what distances and how the pipe system is branched out towards intakes. An approach that avoids these problems is the measurement of the local pressure behind a blocked intake during a simulation of an entrapment.

Figure 1: Top view of a drainage system with two intakes. The flow at intake B stops and the flow in between of point A and C is doubled. The local pressure at point B is equal to the pressure at point A minus the pressure loss ΔP between point A and C.

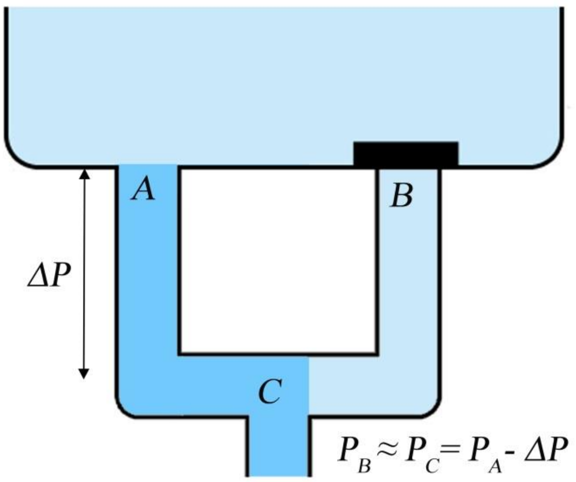
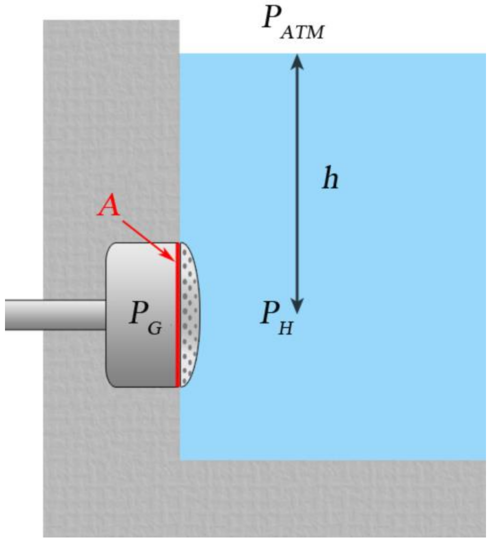


Figure 2: The hydrostatic pressure P_H at a certain depth in the pool and the local gauge pressure P_G behind a drainage intake. Both P_H and P_G are gauge pressures relative to the atmospheric pressure P_{ATM}.



Suction force of drainage intakes

How a person can be trapped by suction to the grate or cover of an intake can be explained by the local differences in pressure. A fluid flows from a higher pressure region to a lower pressure region. Pressure is defined as a normal force per unit of area applied perpendicular to a surface. The suction force on a swimmer blocking a drainage intake can therefore be defined as the product of a differential pressure between two pressure regions and the cross-sectional area of the grate covering a drainage intake (Avezaat, 2013). The highest local pressure (P_H) is situated around the body of the trapped swimmer blocking the submerged intake and is determined by the hydrostatic pressure at a certain depth in the pool, as illustrated by figure 2. This pressure is a positive gauge pressure relative to the atmospheric pressure. The lowest local pressure (P_G) is situated behind the blocked grate of the intake and can be both a positive or negative gauge pressure relative to the atmospheric pressure. The equation for the suction force can therefore be written as:

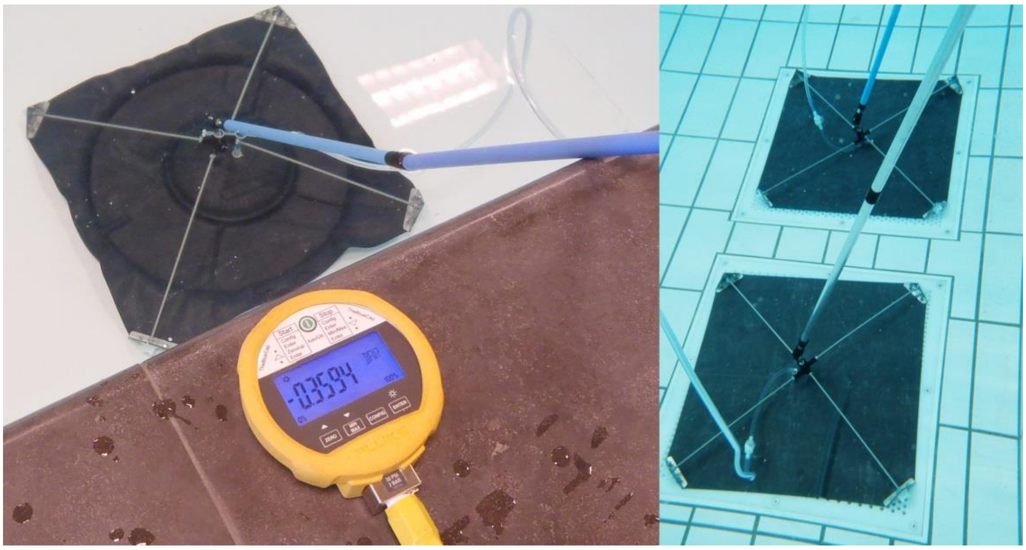
$$F_{SUCTION} = (P_H - P_G) \cdot A$$

With $F_{SUCTION}$ the suction force on a blocked intake in units of newton (N), P_H the hydrostatic pressure and P_G the local pressure behind a drainage intake in units of Pascal (Pa) and A the cross-sectional area of a grate covering a drainage intake in units of square meters (m^2). The space between a grate and the wall or frame is not always hermetically closed. The cross-sectional area (A) is therefore determined to be the entire surface area of the grate covering an intake. This includes the spaces between holes in the grate. In every pool the hydrostatic pressure P_H increases with 9.81 kilopascal for each metre of depth in water. The local gauge pressure P_G behind a blocked grate is an unknown variable. As mentioned earlier, this pressure can be approximated by modeling, but it can also be measured with a pressure gauge during a simulation of an entrapment.

EXPERIMENTAL RESEARCH

For a suction entrapment simulation, the grate covering a drainage intake needs to be blocked by an object that has properties similar to human skin and tissue. The Blue Cap Foundation developed a measurement method in which a drain is blocked by a flexible EPDM rubber cloth with dimensions of 0.5 metre by 0.5 metre. A valve close to the center of the cloth is connected to a pressure gauge with a flexible tube to allow accurate measurement of the local pressure behind a blocked grate of a drainage intake. The measurement method developed by The Blue Cap Foundation is shown in figure 3.

Figure 3: Examples of pressure measurements during simulations of suction entrapment on intakes. On a dome-shaped grate (left) and flat grates (right).

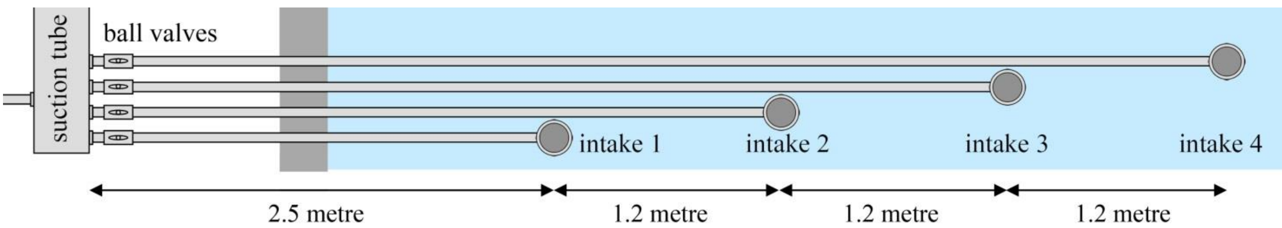


For experimental research a test pool was built to simulate various types of drainage systems. The pool, 6 metres long and 3 metres wide, is filled with water to a height of 0.9 metre from the bottom. The pool contains 12 drainage intakes covered with various types of flat and dome-shaped grates that are commonly used in public and private swimming pools in the Netherlands. A set of 3 self-priming centrifugal pumps, with expected pump capacities of 20 m^3/h, 40 m^3/h and 60 m^3/h, are connected with parallel pipelines to a large cylindrical suction tube. All 12 drainage intakes are connected in parallel with their own pipeline to this suction tube. Each drainage intake could be closed off from the water circulation by closing a valve in the piping system. Volume flow rates and flow velocities could be measured through each pipe section with an ultrasonic flow meter.

Results

The results of an experiment that was conducted in the test pool for a scientific study (Avezaat, 2013) are shown in table 1. In this experiment a section with four conical drainage intakes was used, which were covered by dome-shaped grates with a diameter of 19.8 cm and a domed height of 2.5 cm. Each intake was connected with their own pipeline to a suction tube. From this suction tube the water could be pumped by three pumps. The pipelines to each intake have different lengths as shown in the top view in figure 4.

Figure 4: Conical drains used in all described experiments. The pipelines between the intakes and the suction tube have an inner diameter of 57 mm, the suction tube has an inner diameter of 285 mm and is connected to the pumps.



Four different fully developed flows were established with either one or two of the three pumps running. With ultrasonic flow measurement the different volumetric flow rates through each intake were measured and their sum gives the entire flow rate in the system. Table 1 displays the results of these flow measurements. In turn, each intake was now blocked by the EPDM rubber cloth while the local pressure P_G was measured. During these pressure measurements a fully developed flow was still present through the other three intakes. The results of these pressure measurements are also displayed in table 1.

Table 1: Measured **v**olume flow rate Q distribution of the intakes and pressure P_G after blocking one of the four intakes as displayed in figure 4. The volume flow rates Q are in units of m^3/h. Local pressures P_G are in units of kilopascal.

Q system	*28.3*		*43.0*		*86.4*		*108.4*	
	Q	P_G	Q	P_G	Q	P_G	Q	P_G
intake 1	7.5	0.70	11.1	-2.35	22.3	-22.25	27.9	-29.68
intake 2	7.2	0.51	11.0	-1.64	22.0	-23.86	27.5	-28.86
intake 3	6.9	0.84	10.6	-0.34	21.3	-22.50	26.8	-28.95
intake 4	6.7	1.01	10.3	-1.08	20.8	-19.95	26.2	-24.89

Similar experiments were also conducted with various systems in which only two conical drains were used (Avezaat, 2013). A fully developed flow through two intakes, with an initial volume flow rate Q of 70 m^3/h, could create local negative gauge pressures of -70 kilopascal and higher when one of the two intakes was blocked.

Another experiment was conducted in which a fully developed flow was established through only one intake. The intake was blocked and a pressure measurement was conducted in time with the pressure gauge. The local pressure behind the drain was recorded at intervals of one second while the pump was in operation. The entire flow in the system was stopped, since the only used intake was completely blocked during the pressure measurement. In this experiment the smallest pump was used. Figure 5 shows the graph of this pressure measurement in time. This experiment was repeated with a larger pump capacity of which the results are displayed in figure 6.

Figure 5: Pressure P_G in time after blocking a single drainage intake at an initial volume flow rate Q of 25.5 m^3/h.

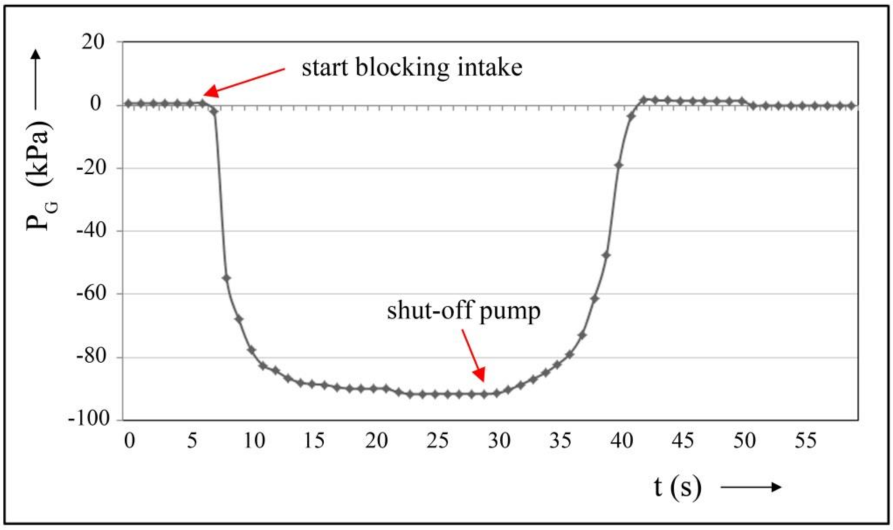
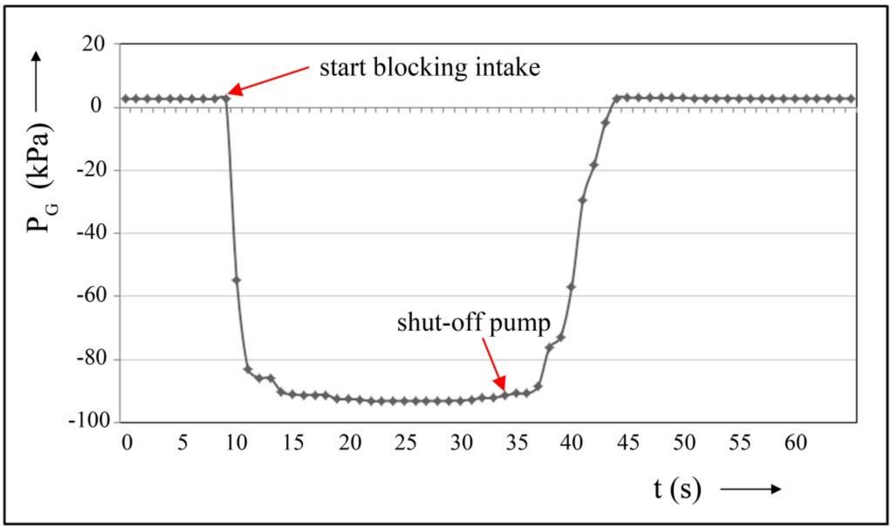


Figure 6: Pressure P_G in time after blocking a single drainage intake at an initial volume flow rate Q of 35.6 m^3/h.



DISCUSSION

Suction and hair entrapment are known to be serious problems in swimming pools worldwide. Entrapment due to high suction forces of submerged drainage intakes or the entanglement of hair on or behind a grate covering an intake increase the risk of drowning. High suction forces due to high negative gauge pressures can also cause serious injuries, e.g. haemorrhages, respiratory problems, disembowelment and heart failure. Through the years, a multitude of technical solutions and safety measures have been developed and implemented in legislation and standards to reduce the potential for entrapment of swimmers (US Consumer Product Safety Commission, 2005; Stender, 2009). Both the European standard EN 13451-3 and the ASME/ANSI A112.19.8 standard in the United States describe similar solutions and safety measures. Examples of solutions include various methods of mechanically or electrically driven systems, e.g. ventilation and aeration of negative gauge pressures, a push-button or pressure-activated emergency shut-off for the pump, pumps with built-in flow reverse systems and a large variety of unblockable, raised and dome-shaped grates. Safety measures include mandatory requirements like the limitation of the flow velocity through a drainage intake, the use of at least two drainage intakes in a water circulation system or the use of at least one additional layer of protection against entrapment.

The experiments mentioned in this study show that swimmers can be exposed to large negative gauge pressures even when more than one drainage intake is used in a water circulation system. Table 1 and other experimental research conducted in a scientific study (Avezaat, 2013) show that the negative gauge pressure that can build up behind a blocked intake is highly dependent on a combination of system properties. The most important system property is the pressure loss in pipe sections of the water circulation system, which can increase significantly with an increased flow velocity when an intake is blocked by a swimmer. The flow velocity is directly influenced by other system properties like the amount and layout of drainage intakes, the volume flow rate in the system and the lengths and diameters of pipe sections. The results of experiments with systems containing only a single drainage intake show that negative gauge pressures higher than -90 kilopascal can be achieved with both low and high pumping power. As shown in the graphs of figure 5 and 6, a very high negative gauge pressure is achieved in a shorter period of time with higher pumping power and higher volume flow velocities. In both cases, victims would have no chance to free themselves as high negative gauge pressures built up within seconds after the intake is blocked.
Pool construction is a competitive market. Especially pools from hotels and aqua parks at popular holiday destinations are built as cheaply as possible. Thin pipes are used for circulation systems to

save materials at the expense of safety against entrapment. Faulty plumbing might therefore be the main reason why so many entrapment accidents are reported at hotel pools and aqua parks (Avezaat & Göb, submitted). However, a large part can also be blamed on a lack of awareness and knowledge about the risks of entrapment, incomplete safety inspections and a lack of responsibility of pool owners. Several studies have shown that many pools are poorly maintained and that these can be life-threatening for swimmers (Davison & Puntis, 2003, Avezaat & Göb, submitted).

Current safety inspections, if any are done at all, are largely based on visual observations. Faulty plumbing cannot be detected by a visual observation only, especially when water circulation systems are located under or encased in a layer of concrete. The presence of a safety measure is often sufficient enough to comply with legislation and standards. However, there is no safety check to test to what extent the implemented safety measure reached the desired goal of reducing or preventing suction entrapment. It is highly questionable whether electrical and mechanical driven safety measures are equally effective a few years after they have been installed. These systems are exposed to a humid environment and dirt and in time their sensory perception might decrease.

European Standard 13451-3 describes some tests with which the risks of suction and hair entrapment can be investigated. The hair test described in this standard has proven to be very effective in locating hair entrapment risks. However, several studies have shown that the permitted flow velocity through the grate covering an intake should be reduced from 0.5 m/s to 0.3 m/s (Mersmann, 2012, Avezaat, 2013). Experimental research in both studies has shown that this directive for the flow velocity occasionally conflicts with another directive in the same standard that states that the permitted tensile force to pull the hair probe from the drain is 15 newton. The European standard EN 13451-3 also describes an obstruction test for the grates covering a drainage intake. A test device as displayed in figure 7 is lowered on the grate of an intake and the test is passed when the test device can be pulled easily from the intake under a specified load. This test has major disadvantages. The test can only be conducted on intakes located in the pool's floor and injuries that can be sustained due to negative gauge pressures are not taken into account. The thin foam slab of the test device has hardly enough deformation possibilities as one would expect from human skin and tissue. Human skin becomes stiffer with age and the skin of children is known to be more stretchable than that of adults (Moronkeji & Akhtar, 2015). The dimensions of the test device, as shown in figure 7, are highly questionable as these are described to be based on an 8-year-old child. It is peculiar that this European standard only attempts to ensure the safety of children of a certain age with certain body dimensions and that the safety of older swimmers is excluded.

Figure 7: Test device of obstruction test as described in European Standard 13451-3. Many commonly used grates in swimming pools cannot be fully blocked by the test device.

The pressure measurement method developed by The Blue Cap Foundation has proven to be an effective tool to detect the presence of high negative gauge pressures in water circulation systems. Current assessments of suction entrapment are based on the flow velocity through a grate covering an intake and the ability to free oneself from the intake. This study has shown that many system properties influence suction entrapment and that entrapment risk can vary significantly in each pool. Measurement of negative gauge pressures, in any way, is a necessity to ensure that entrapment is excluded and that the safety of swimmers is guaranteed in each pool.

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