

WATER FLOW REDUCTION AND AIR BUBBLE GENERATION MECHANISMS IN NARROW INTERFACES SUCH AS CONCRETE CRACKS

Muzafalu KAYONDO*¹ and Toshiharu KISHI*²

ABSTRACT

Water flow between two parallel plates has been previously studied in fluid mechanics. Based on the same models, Poiseuille's equation has been modified and used to clearly estimate water flow between two parallel surfaces such as concrete cracks. Recent findings in the use of water permeation to evaluate extent of self-healing concrete for a stagnant and penetrating crack have pointed to the blocking effect of large air bubbles. It negated the contribution of the traditionally known self-healing mechanisms during the first few days of water supply. The findings pointed to growth of air bubbles as the main cause of the drastic water flow reduction in the initial stages of water supply. In the follow-up research, water flow reduction has been observed to occur even in the absence of largely visible air bubbles, and within less than 5 hours of water supply. By using equilibrated air saturated water (incapable of growing any large air bubbles) in the current research, water flow reduction was observed to decrease by about 20-30%. This reduction is attributed to micro and nano size air bubbles that are strongly fixed (or trapped in the microstructure) on the surface of concrete. Once formed and fixed there, they cause water flow braking, which is observed in the form of reduced water flows.

Keywords: Narrow interfaces, Water flow, Self-healing, Airbubbles,

1. INTRODUCTION

Water flow between any two points was greatly investigated by Darcy [1] and Poiseuille to mainly be influenced by the hydraulic gradient/pressure difference.

$$q = KA \frac{h_2 - h_1}{l} \quad (1)$$

In Eq. 1, the flow rate q is experimentally determined to be equivalent to the product of hydraulic gradient $(h_2 - h_1)/l$, and cross-sectional area, A ; K is the hydraulic conductivity of the porous material.

$$q_r = \frac{\xi \Delta p \cdot b \cdot w^3}{12 \eta \cdot d} \quad (2)$$

In Eq. 2 the flow rate q_r through rough concrete cracks can be estimated by including a material roughness factor ξ to the Poiseuille parallel plate equation. Δp is the differential water pressure between inlet and outlet of crack, b length of crack (equivalent to specimen width), d is flow path of crack (specimen height), and η is absolute viscosity.

In the modified Poiseuille's law Eq. 2 [2] for parallel plates (such as concrete cracks), and Darcy's law, material characteristics are mentioned to play a role. Fluid characteristics too such as viscosity affect

water flow through porous media or concrete cracks.

In consideration of self-healing concrete where the formed cracks are capable of precipitating healing products that close the cracks, water flow reduction is expected to solely be a result of crack narrowing. Precipitated cementitious products across the surface reduce the cross-sectional area of the water flow path. And in Eq. 2, consequential water flow reduction is expected to occur [3].

For the narrow gaps of concrete cracks, the traditional mechanisms such as CaCO_3 precipitation, swelling, sedimentation and hydration of unhydrated cement have been linked to crack closure and consequently water flow reduction. However, these mechanisms have been ruled out to be responsible for the initial drastic water flow reduction (Fig.1) in self-healing concrete cracks. Instead, formation of large air bubbles, observed through a direct visual approach of water flow has been noted to cause the rapid initial water flow reduction [4], (Figs. 2 & 3.)

In water purification systems that rely on sand percolation as a filtering mechanism, effluent flow has been observed to be affected by the quality of water (in terms of Total Dissolved Gasses, TDGs). Air bubbles grow until a certain level to cause burping in the system (Fig.4). Effluent flow is reduced when there are more TDGs in the system [5]. The flow is observed to vary with time passing (even in as less as 4 hours).

*1 Graduate School of Engineering, The University of Tokyo, JCI Student Member

*2 Professor, Institute of Industrial Science, The University of Tokyo, Dr.E., JCI Member

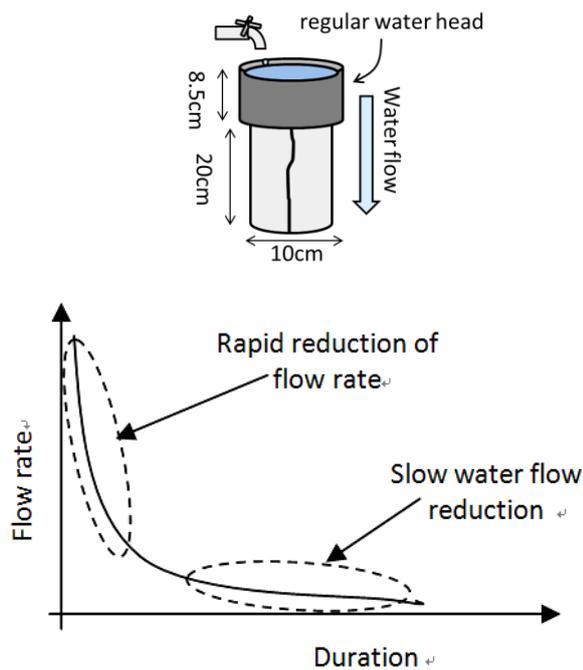


Fig.1 Typical water flow test set-up and flow curve

These results are similar to what Ikoma [4] observed through a direct visual approach of water permeation in narrow concrete cracks. While maintaining a constant water head, water flow rate varies. Based on Darcy's equation and for a standard homogenous material, plus a constant hydraulic gradient, there is an expected constant flow rate outflow for porous media. In the modified Poiseuille's equation too, when all variables are made constant, any water flow reduction is expected to be a result of narrowing crack width (for self-healing concrete). In reality, within the first few hours of water supply, there isn't any noticeable self-healing to cause over 30% crack width reduction. However, water flows are observed to plummet by over 40%. Formation of air bubbles (observed through a visual technique) was highlighted to be responsible for the reduced water flows.

Extended understanding of how this air bubble phenomenon occurs has been extensively studied [6] to reveal the necessary conditions for its inception, plus its continued effect in concrete cracks. The significance of this research is to further understand water flow reduction in narrow interfaces such as concrete cracks.

In this research, further visual observation of water flow in mimicked narrow gaps of concrete has been continued. With the knowledge of the fact that air bubbles evolve from water, effect of different water types has been studied. Of most interest is when less than 100% air saturated water is used, and water flow reduction is still observed – even in absence of large or visible air bubbles. This is contrary to previous understanding (of water flow reduction due to blocking effect of large air bubbles in concrete cracks) [4].

Water is known to contain nano and micro air bubbles (invisible to the naked eye), depending on the balance of several factors at play. The results of this

research reveal the effect of these nano and micro air bubbles, either originally contained in water, or formed during water flow in the rugged narrow interfaces. Once formed, these nano and micro air bubbles may be strongly fixed to the rugged micro pore structure of the concrete surface. When held strongly on these interfaces, they cause water flow braking, which we observe in the form of reduced water flows with time. If supersaturated water is substituted in place of equilibrated water, these stable nano and micro bubbles are capable of growing into bigger bubbles that further contribute to water flow reduction (by blocking effect)

The mechanisms of air bubble creation and growth start with the basic necessary conditions of 1) existence of a narrow gap where water flows, 2) The quality of water (containing dissolved air or not), 3) surface properties of two parallel boundaries, and internal water flow hydrodynamics. Any observed bubble growth is due to air exchange at the air bubble – water interface.

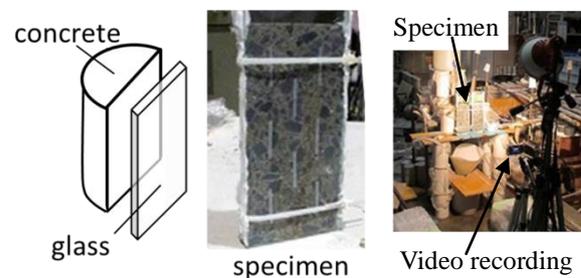


Fig.2 Set-up adopted for direct visual observation of water flow in simulated concrete crack surface

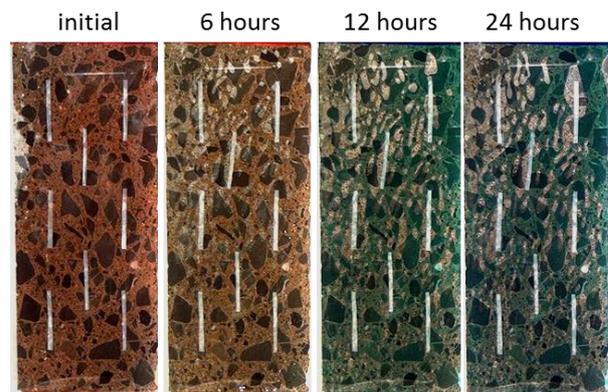


Fig.3 Air spaces observed to develop with continuous water flow in concrete-glass interfaces.

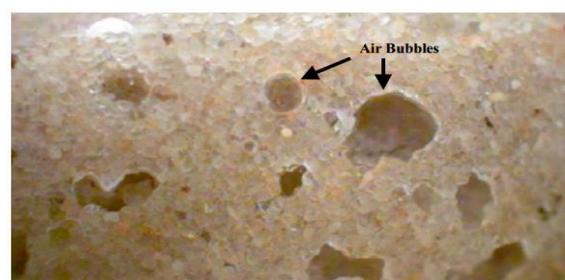


Fig.4 Air bubbles in sand filtration media for super saturated waters at water treatment facility [4]

Characteristics of this interface in such narrow spaces are still not clearly understood. Some literatures [7], [8], and [9], point to the air – water interfaces having properties completely different from the bulk water. Properties of water such as surface tension may be different at the interface than in the bulk. This could all point to why in such narrow gaps, with the right conditions, air bubbles tend to grow instead of maintaining their stable smaller sizes.

In this research, water flow reduction is observed within a small duration of water supply. More still, in the absence of any visible air bubbles as earlier noted. The growth mechanism starts with the necessary conditions, and also includes the air bubble interfacial behaviour. There may now be necessity to include this new effect of air bubbles to further understanding, depending on the situation of water flow.

The scope of air bubble mechanisms in this investigation excludes and is different from other phenomenon of air bubbles, such as cavitation or boiling. It mainly deals with a rather contradictory phenomenon of air bubble growth instead of shrinkage and disappearance while in water. Air bubbles are more stable in their smaller nano to micro sizes; beyond these sizes, they either shrink and disappear or rise out of water. However, what we observe in narrow gaps such as concrete cracks, and having water flow, is that air bubbles continue to grow and yet remain stable.

2. INVESTIGATIVE APPROACH

2.1 Specimen Preparations.

As a methodology, self-healing test specimens are usually first cracked either by splitting or bending tests. The introduced crack simulates what would happen in actual conditions. In most permeation tests, a static penetrating crack is introduced and water supply provided through one surface normal to the crack. The flow-through water is collected and its volume measured. It is this volume reduction that is indicative of the extent of self-healing (Fig. 1). In this research, a procedure of direct visual observation is adopted. This is so as to observe what happens inside the crack narrow gaps as water flows through. In case of concrete, a cylindrical concrete specimen is machine cut along its length. A glass plate is then attached on the flat machine cut concrete surface, leaving a gap dictated by the thickness of Teflon sheet (0.1 – 0.2mm). By using silicone adhesive, the glass-concrete boundaries are sealed.

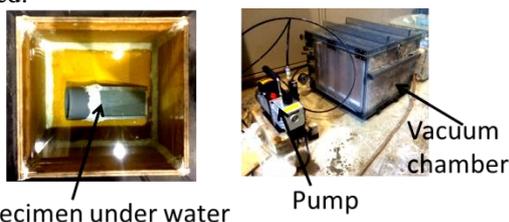


Fig.5 Vacuum soaking of specimens before start of water flow tests. (White substance at the end of arrow is silicone adhesive to attach PVC pipe, left)

An 8.5cm PVC pipe is then attached (Fig. 5) with white silicone adhesive.

The PVC is used to maintain a constant water head during the water supply regime.

Besides concrete, other materials such as concrete, mortar, cement paste, dented aluminium plate, pumice surface and wood were investigated understand this phenomenon. With these other materials, flat surfaces that can be bound to glass are used. In the case of aluminium, a plane plate is dented with uniform non penetrating crevices across its surface as in Fig. 6.

2.2 Specimen Initial Conditions.

Once the silicone has dried, the set-up is ready and the specimen is rid of any air that may be contained inside the system. For concrete and pumice specimens, vacuum soaking for 12 hours is performed. For other material specimens such as Aluminium plate, vacuuming for 6 hours is done.

Fig. 5 shows an Aluminium plate specimen under de-aired water and ready for vacuuming. White silicone adhesive connects the bottom part of the specimen to the PVC pipe. De-aired water is applied initially before supplying any study water type. All this is done to remove any trapped air bubbles within the specimen, and to initiate flow response in the direction of water flow (1-D flow).

2.3 Water flow measurements and visual observations.

To understand the changing water flows, measurements of flow-through water are taken at every 15 minutes interval. By specifying this measurement interval, we are able to capture the smaller time variations of water flow. In most of the measurements, 90 minutes total duration is considered. Follow-up measurements at 3h, 5h, 7h, 12h, up to 24h are taken, for comparison purposes only.

At the same time of continued water permeation, video recording across the observable surface is done. This is in addition to critical observations by human eye. Coloured water may be added from time to time to clearly see the outline of the formed air bubbles. The position, shape, and size of an air bubble are identified by its colour difference once colored water is supplied. Additionally, detailed observation via video is done to clearly understand how air bubbles evolve.

Additionally, magnified images of a single growing air bubble, plus water flow profiles have been studied to understand the mechanisms involved.

3. RESULTS AND DISCUSSIONS

3.1 Effect of Material types

Having observed the air bubble generation phenomenon first with concrete surfaces, other material surfaces were investigated. By following the same specimen preparation technique, materials such as pumice, aluminium plate (smooth and dented), were tested. They showed similar results as concrete material surfaces. In this research, water flow results using concrete specimens are shown.

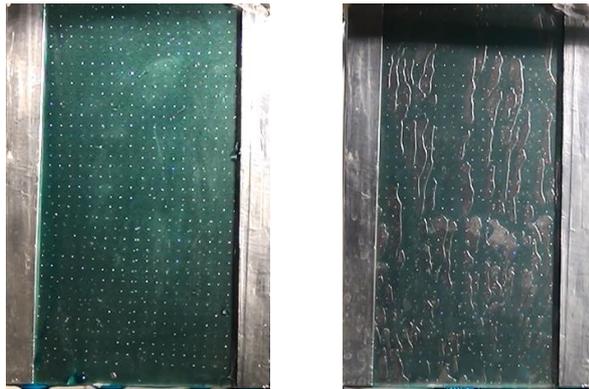


Fig.6 Air bubbles formed between interfaces between dented Aluminium plate and glass plate

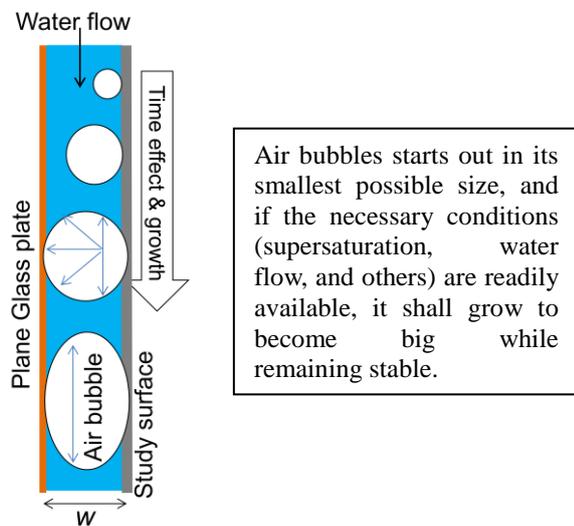


Fig.7 Schematic of air bubble growth within the narrow gaps – a side view

In the case of Pumice, it comes with a naturally porous surface. For study purposes, a pumice surface measuring 100x150x20mm was used parallel with glass (leaving a crack allowance of 0.1 - 0.2 mm) to study the same phenomenon. Similar air bubble development was observed; air bubble growth occurred faster for pumice compared to other materials. Water flow reduction was not measured due to extended porous nature of pumice.

For Aluminium, the smooth plate was used as a control and another dented with 0.3mm non penetrating holes. The dents were imparted on the surface of aluminum to simulate surface imperfections or pore on concrete surface. Fig. 6 shows the air bubble evolution on a dented Aluminium plate. Fig. 7 shows the growth process of an air bubble from the side view.

On the other hand, the un-dented Aluminium (considered to be smooth) produced no notable air bubble phenomena. Continued observation of air bubble formation revealed a constant pattern of air bubble formation. Air bubbles mainly formed at the pores or crevices of the study material. The dents formed the base and acted as a hinge for the air bubbles. This is due to the low energy requirements at such points.

3.2 Water flow measurements and air bubble growth.

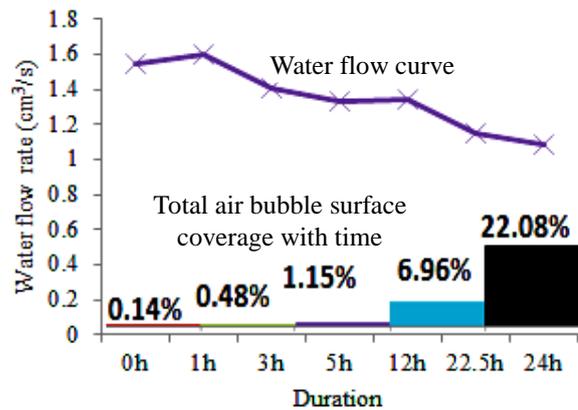


Fig.8 Correlation of water flow reduction and air bubble growth for concrete specimen

Water flow measurements were performed in shorter time intervals to reveal smaller and consistent water flow changes. Fig. 8 reveals a correlation of water flow reduction with air bubble growth. Air bubble growth is computed as a percentage of total water flow surface area that is covered by air bubbles. Volume of flow-through water collected in five minutes is measured and flow rate calculated. Air bubble growth and development has a negative correlation with water flow reduction.

3.2 Water Flow Reduction in Absence of Visible Air Bubble Growth.

In similar water flow tests, where water having equilibrated dissolved air content was used, it was possible to continue observing water flow reduction. The main difference was that this time, no noticeable air bubble growth was observed. There was still however, a mechanism by which water flow was continuously reduced within the first few hours of water supply.

In Fig. 9, water with just less equilibrated dissolved air content was used after specimens were vacuum soaked and prepared as described in section 2.2. About 15% water flow reduction was observed with this amount of water flow. This observation of water flow reduction in absence of visible air bubbles cannot be explained with the traditional self-healing approaches, or the effect of air bubble blocking of water flow.

However, understanding air bubble formation, growth, and stability within narrow interfaces gives a clue as to how this water flow reduction takes place. Air bubbles usually prefer to maintain a stable size (of a few hundred nanometers), and once formed and within interfacial surfaces, they become strongly fixed (or trapped) within the porous structure of concrete surfaces or any imperfections on any surface where they are formed.

Once fixed and strongly held at their position, they cannot easily be washed out by flow-through water.

Instead, in their stable condition, they cause water flow breaking which is exhibited in terms of reduced water flows. Fig. 10 depicts these so many micro and nano size air bubbles not being able to cover the entire gap of water flow, but still cause notable water flow chocking.

For interfaces where air bubbles have not been observed to form, such as plane Aluminium-glass or glass-glass surfaces, such water flow reduction is not observed as long as consistent conditions are maintained.

This water flow reduction that still occurs under constant hydraulic gradient, was not been catered for in Eq. 1 & 2. Even when material factor or reduction factor is catered for, the multiphase combination effects of water flow seems to be left out. For example how water interacts with crack surfaces to cause air bubble growth which then leads to changed flow-through rates. This leads to unsteady state flow which conflicts with Poiseuille assumption of steady state conditions being maintained.

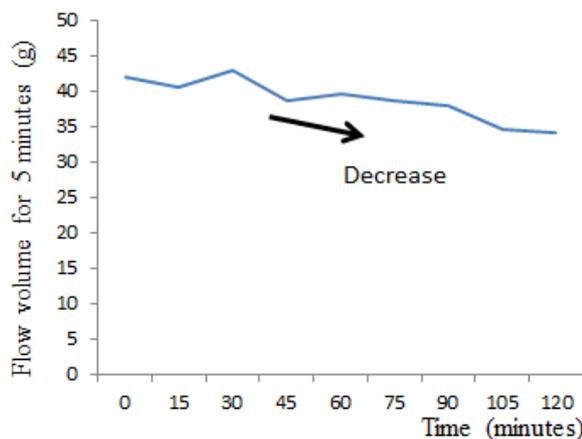


Fig.9 Water flow reduction graph using equilibrated air content water, for concrete specimen

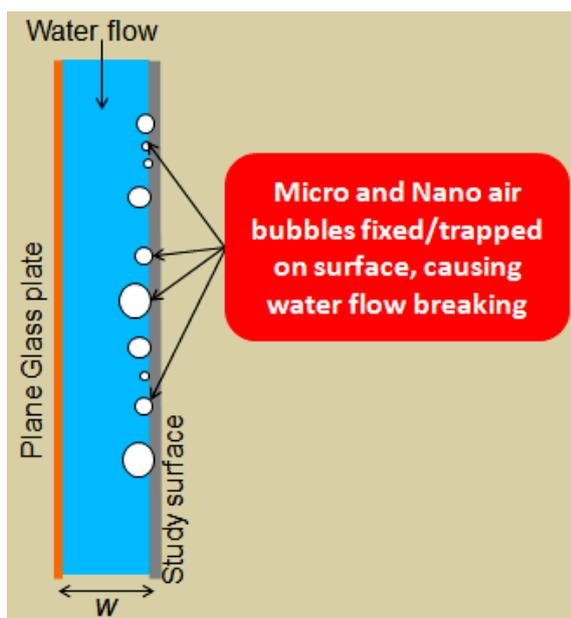


Fig.10 Nano and micro air bubbles fixed/ trapped in the surface structure of study material

3.3 Effect of water quality on water flow

The quality of permeating water will in a way affect water flow especially in narrow gaps where various properties of water may be heightened. In part of this research, to investigate factors that affect air bubble growth, alkaline and acidic water was used to study both water flow reduction and possible air bubble growth. Dilute sodium hydroxide solution and hydrochloric acid were used to make dilute solutions of alkaline and acidic condition (pH values of 10 and 3 respectively).

In these experiments too, just less equilibrated air saturated water was used to make the solutions. Fig. 11 shows the water flow reduction graph using the alkaline solution. Water flow reduction occurs until one hour where it starts to flatten out. On the other hand, Fig. 12 shows flow curve with acidic water. In Fig. 12 water flow reduction continues on until 1.5hours, at which time sub millimeter order air bubbles could be identified by the naked eye. The onset of visible air bubbles (of about 100micron and greater) marks the end of stable and non-growing micro and nano bubbles.

From this observation of possible air bubble growth using acidic water (which has less dissolved air than it would contain at equilibrium), it could be considered that acidic conditions may favour air bubble growth in narrow gaps having water flow.

For all water conditions, a dissolved oxygen (DO) meter was used to measure oxygen concentrations (percent saturation) of the dissolved air content in water.

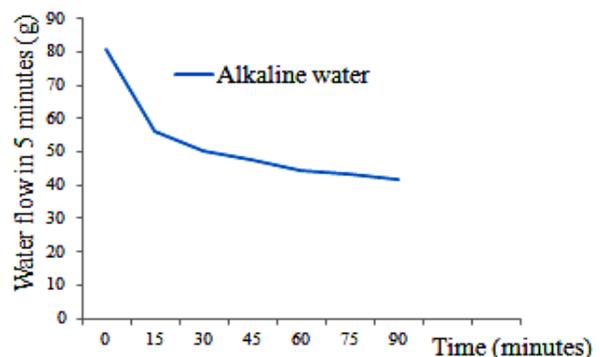


Fig.11 Effect of equilibrated air content alkaline water on water flow for concrete specimen

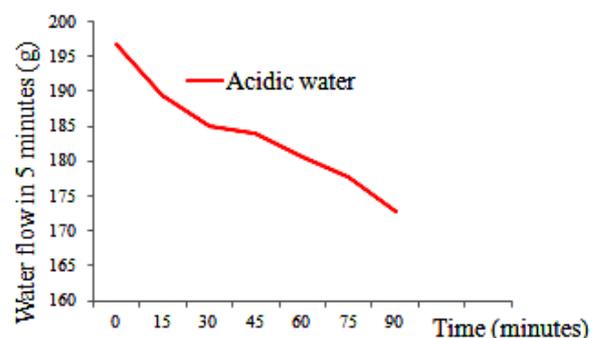


Fig.12 Effect of equilibrated air content acidic water on water flow for concrete specimen

For water flow through narrow interfaces such as concrete cracks, it's not only total dissolved air that determines the resulting air bubble growth or water flow reduction, but also other parameters such as pH of flow through water.

4. MECHANISM AND AIR-WATER INTERFACE

It has greatly become quite clear that the air bubbles evolve from the air contained in water [6]. Within the narrow interfaces having the necessary conditions, air bubbles will easily develop. Among these necessary conditions is water super saturation, presence of nucleation sites, water flow condition, plus other action mechanisms at the air bubble-water interface.

Once the air bubble is formed, the continued presence of air saturated water becomes a dominant factor for continued air bubble growth. The air bubble stays stably hinged at the nucleation site or may become washed out depending on the balance of forces at play. Once formed, air bubbles start dictating the water. Also, while two adjacent air bubbles are growing, they may attain sizes that physically force them to merge and become one larger bubble.

In Fig. 13 the air bubble interface is depicted to be that boundary that separates flowing water from the bubble air. It is this interface that allows for exchange of gases to and from the water into the air bubble, depending on the balance of necessary conditions.

In reality, the air-water interface is one of the biggest interfaces that make up the earth, since it is covered by almost 70% water that is open to atmospheric air. Understanding this thin interface is still both a mystery and point of controversy among many researchers [7], [8], [9], and others. And yet many believe that understanding the arrangement of water molecules, their orientation, and clustering would be a great step to uncovering the mysteries of water.

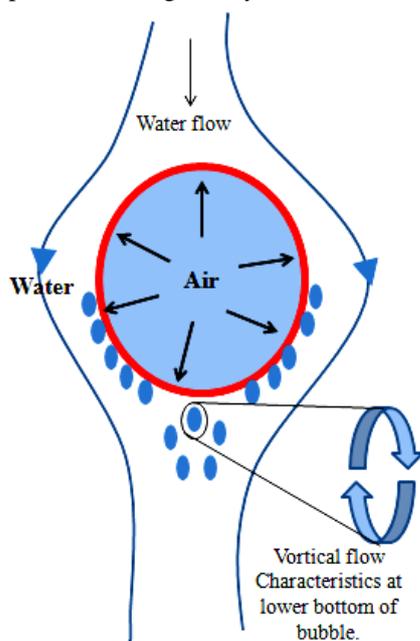


Fig.13 The air bubble - water interface: exchange

boundary for gases

5. CONCLUSIONS

- (1) Water flow reduction has recently been attributed to large air bubble blockage of water flow paths. In this research findings, invisible micro and nano air bubbles that are fixed/trapped in the material surface structure equally cause significant water flow braking effects, leading to reduced water flows. The combined effect of crack roughness and water type may need to be considered in estimation of theoretical water flows using the modified Poiseuille equation.
- (2) Air bubble growth in narrow interfaces with water flow requires presence of nucleation sites, water super saturation, and other water flow hydrodynamic mechanisms. The air bubble - water interface behavior in narrow gaps is also hypothesized to influence air bubble growth within such interfaces.

ACKNOWLEDGEMENT

This work was supported by JSPS KAKENHI Grant Number 25249060.

REFERENCES

- [1] Darcy, H., "Les Fontaines Publiques de la Ville de Dijon", Dalmont, Paris, 1856.
- [2] Massey, B.S., "Mechanics of Fluids", 8th Edition, Taylor & Francis, 2006, pp. 199-205
- [3] Edvardsen, C., "Water permeability and Autogenous healing of cracks in concrete," ACI Materials Journal, V.96, No.4 July – August 1999, pp.448-454
- [4] Ikoma, H. et al., "Elucidation of Rapid Reduction of Water Flow through Concrete Crack Regarded as Self-healing Phenomenon," ICSHM2015, June 22-24, 2015.
- [5] Scardina, P. and Edwards, M., "Air Binding of Granular Media Filters", Journal of Environmental Engineering, ASCE Vol.130, No. 10, October 2004, pp. 1126-1138
- [6] Kayondo, M., Sato. S. and Kishi. T., "Detailed observation of air bubble generation by water flow hydrodynamics in narrow gaps such as concrete cracks," ICSHM2015, June 22-24, 2015.
- [7] Chaplin, M., "Theory vs Experiment: What is the surface charge of water?" Dep't of Applied Science, South Bank University, London, doi: 10.14294/WATER.2009.2
- [8] Stirnemann, G. et al, "Water Re-orientation, hydrogen-bond dynamics", Royal Society of Chemistry, Vol.146, 2010, pp.263-281
- [9] Maoyuan, L., Beattie, K. J. and Weale, G. A., "The Surface Relaxation of Water", ACS, Journal of Physical Chemistry B, 2012, Vol. 116, pp.8981-8988