The detection of porous media volume using the modified Archimedes method

MASOUD OSFOURI ▪ Institute of Energy, Ceramics and Polymer Technology, Faculty of Materials and Chemical Engineering, University of Miskolc
ANDREA SIMON ▪ Institute of Energy, Ceramics and Polymer Technology, Faculty of Materials and Chemical Engineering, University of Miskolc

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Masoud OSFOURI
is PhD student in material science and works on foam glass and light weight concrete at the University of Miskolc in Hungary. His background is mechanical engineering and his MSc thesis dealt with shape memory alloys and fiber metal laminates. He received his MSc degree in applied mechanics in 2017 at the University of Zanjan. His actual research topics are foam glasses, polymer matrix composite materials, and lightweight concrete.

Andrea SIMON
works full-time at ZF Hungary Ltd. as a supplier development engineer, and part-time at the University of Miskolc as an associate professor. She received her PhD degree in materials science and engineering in 2010 at the University of Miskolc. Her actual research topics are foam glasses, waste recycling, and microstructural characterization.

Abstract

Foam glasses are novel materials in engineering that have found a special place in various industries during recent decades. Foam glass is generally produced using recycled glass. By using waste materials, in addition to reducing the amount of waste glass that can harm the environment, it is possible to achieve a lightweight foam that is resistant to compression, corrosion, and heat transfer. The foam glass structure consists of cells that are filled with gas, and the walls of these bubbles are made of solid glass. One of the challenges is to measure its density. Because the samples made in the laboratory generally do not have a conventional shape, and therefore it is difficult to find the volume of the samples geometrically. In this paper, a new, simple, and practical method to find the density of foam glass is presented. The result of the tests showed a very good coincidence between geometrical volume measurements and volumes measured by using this novel method.

Keywords: glass foam, volume, modified Archimedes method, porous materials
Kulcsszavak: üveghab, térfogat, módosított Archimédeszi-módszer, porózus anyagok

1. Introduction

Foam glass is a porous material with a glassy skeleton in which the holes are surrounded by thin glass walls and separated from each other. Foam glass has a unique combination of properties: lightweight, rigid, and strong, compression resistant, thermal insulation, non-flammable, chemically neutral and non-toxic, resistant to rodents and insects, resistant to bacteria, water, and humidity. In addition, it is easy to install, cut, and drill, and it is easily combined with concrete. This combination of properties makes foam glass indispensable in the construction and petrochemical industries (oil and gas transmission lines), railroad foundations, dam constructions, foundations of streets and highways, sports fields, and many other fields [1].

In the process of making foam glass, firstly the waste glass is ground and turned into fine glass powder. Then the powder is mixed with a foaming agent. The mixture consisting of glass powder and foaming agent is heated to a temperature at which the reaction of the foaming agent begins. The product of this reaction is gas that results in a large number of small spherical bubbles, and a cellular structure is created. After cooling, that structure forms the pores of the foam glass [2]. The properties of foamed glass products strongly depend on the type and amount of foaming agents and other additives, the particle size of the components, and the sintering conditions.

If the composition of the glass is such that it crystallizes during the production process, the possibility of the formation of closed holes will be reduced, and as a result, the quality of the final foam glass will be reduced. Therefore, the preparation of foam glass (with closed porosity) is not easily possible and requires extensive research to determine the optimal temperature of sinter-crystallization in relation to the temperature of gas exit from the material [3]. The glass softening temperature should always be lower than the foaming reaction temperature. But if the composition of the glass is prone to crystallization and the crystallization speed exceeds the sintering speed of the glass, then the crystallization of the glass will increase its viscosity, and as a result, the softening temperature of the glass will be higher than the temperature of the gas exiting the sample. In this case, the possibility of creating closed porosity in the foam glass is reduced, and open porosity increases [3, 4].

The importance of energy conservation on the one hand and the need to lighten the buildings, on the other hand, make the use of lightweight, heat, and sound-insulating but strong and stable materials in building construction more and more essential. But for being an applicable material, they require to be a low cost as well [5].

The production of foam glass dates back to the 1930s, when major research activities were carried out throughout the industrialized countries; Due to the numerous patents filed during the same period, it is not clear who were the first inventors of foam glass. The foam glass production method can be divided into two basic types, production of foam glass by sintering the above-mentioned finely ground glass powders with a suitable foaming agent and direct blowing of fluids (air, CO_2, water vapor) into molten glass [6]. Since in the research field mostly the researchers made small specimens and do different tests on them, finding the apparent volume of specimen is a big deal in the experimental research fields. There are some methods which researchers used for finding the volume of irregular shaped specimens.

In some research, they used the conventional Archimedes method for measuring the volume of irregular foam glass specimens [7-9]. When using the conventional Archimedes method, there is inaccuracy in measuring the changed level of liquid by sinking the foam specimen. This problem leads some of the researchers to use other methods, for example a gravimetric method with using pycnometer to find the density [10-14]. The pycnometer could be used as an applicable method for finding the volume of micropores but there is a need to mill the specimen to fine powder and then use that method [11]. Thus, it is a destructive method, and it could not be useful in all the research in order to find out the foam appearance volume.

All in all, as it is clear one of the most important issues in the field of porous material research is to measure the volume of irregular shape specimens. because it becomes difficult to measure due to the porous structure and irregular shape of the samples [15]. 3D scanning is a suggested method to use in order to find the volume of irregular porous foam glass [16, 17]. Since this is a time and money consuming method, there is no report regarding use of this method in the field of foam glass volume determination. As a summary, using three-dimensional scanning methods, photography and image analysis methods, and conventional Archimedes measurement methods and finding the volume by geometrically measurement method, the researchers determine the volume and subsequently the density of the foam glass. In the case that the sample is small and its shape is irregular, the mentioned methods could be ineffective or have low accuracy [18-22]. So, there is need to establish other methods to find the volume of foam glass with high accuracy, low time and money consuming. This research is explaining a modified Archimedes' method to detect the irregular volume of foam glass in a short time, low price and very easy way.

2. Theory and methods

To introduce this method, the theory of the subject has been discussed first. The volume (V) of an irregular shape substance is required. For this purpose, firstly the mass of this substance will be measured using a scale. Let the measured mass to be m_{dry}.

Now, this substance is immersed in water. The water pressure on the surface of this substant could be calculated by considering a cubic element of the sample whose length, width, and height are dx, dy, and dh, respectively.

The pressure exerted on the surfaces of this element is normal to the surface and at any point this pressure is $p=\rho gh$ where h is the distance from the free surface of the fluid, ρ is the density of the fluid at the test temperature and g is the gravity constant.

Considering that at equal heights (h), the pressure of the fluid is constant, therefore, in the element of the *Fig. 1B* (right side), dp_x and dp_y are equal to zero, so two pressures equal to dph_2 are applied to the element in opposite directions on the $dh \times dx$ and $dh \times dy$ surfaces, which cancel out each other.

However, along the height or h direction of the element, dp_h have a value equal to $\rho g(dh)$, and considering that the height of the bottom of the element from the fluid free surface is higher than the height of the upper surface of the element from the fluid surface, therefore, the total pressure will be upwards and its value is $\rho g(dh)$.

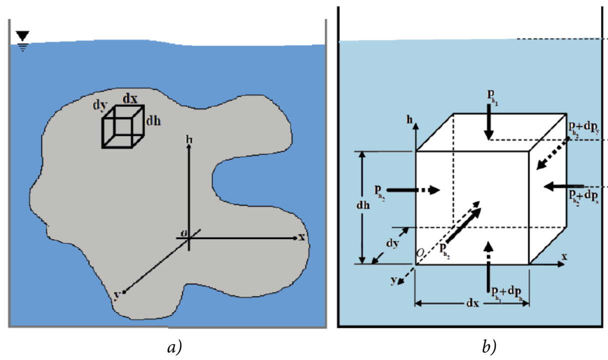


Fig. 1 The irregularly shaped object immersed in water(a) an element and hydrostatic pressure on its sides (b)
1. ábra Szabálytalan alakú tárgy vízbe merülve (a) és egy elem a hidrosztatikus nyomás jelölésével (b)

This pressure is applied on the $dx \times dy$ surface, so the amount of force corresponding to this pressure is equal to:

$$dF_b = \rho g(dh) \times dx \times dy \tag{1}$$

And the volume of this element is obtained by multiplying its lengths together, therefore:

$$dV = dh \times dx \times dy \tag{2}$$

So, *Eq. 1* can be rewritten in this way.

$$dF_b = \rho g \times dV \tag{3}$$

By taking the integral from both sides of *Eq. 3* and keeping in mind that ρg is a constant number, the upward buoyancy force applying to the object is obtained.

$$\int_V dF_b = \rho g * \iiint_V dV \Longrightarrow F_b = \rho g V \tag{4}$$

Therefore, by measuring the buoyancy force of a material in a fluid with a certain density, the volume of that material can be obtained.

Now, considering that foam glass consists of open and closed pores, it should be noted that with this method, the total volume of the foam glass solid skeleton and closed pores can be calculated. To calculate the volume of open pores, the amount of water absorption into the foam glass sample should be obtained.

To calculate the volume of foam glass, first consider a cage like in *Fig. 2*. When this cage is empty, we immerse it in water and connect it to the scale to measure the immersed weight.

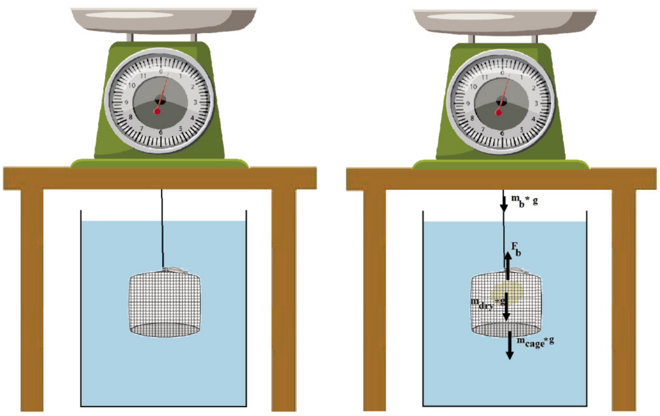
In this way, weight of the floating cage in the water is obtained. Let's call this force mcage. To measure the volume of open pores of the foam glass, firstly the foam glass is boiled in water for 2 to 4 hours. This will cause the open pores to be filled with water. After this step, it should weigh the water saturated foam glass and name this weight as m_{wet}.

The volume of open pores is easily calculated through the following formula.

$$V_{Open\ porosity} = (m_{wet} - m_{dry})/\rho_{water} \tag{5}$$

Now, to calculate the volume of the skeleton and the closed pores, the water-saturated specimen is put into the cage and immersed it in the water. If the density of saturated foam glass is higher than water, then the foam will sink into the water and the scale will show a number higher than the mcage. Otherwise, it will exert an upward force on the cage and the scale will show a number lower than the m_{cage}. In any case, we consider the number displayed by the scale as m_b.

Now, if the free graph of the foam glass and the cage is drawn (*Fig. 2-B*) and the equilibrium relations is written, the *Eq. 6* will be obtained.



a) *b)*

Fig. 2 Empty cage weighing in water (a). The free body diagram of the foam glass and cage in the water (b)
2. ábra Üres ketrec mérlegelése vízben (a). A vízben lévő üveghab a ketrecben (b)

$$m_b g = m_{dry}\, g + m_{cage}\, g - F_b \quad (6)$$

$$F_b = (m_{dry} + m_{cage} - m_b)\, g \quad (7)$$

By replacing the F_b obtained from *Eq. 7* in *Eq. 4* the following formulation for the volume of foam glass (skeleton plus closed porosity) is obtained. Let's call this volume V_1.

$$V_1 = \frac{m_{dry} + m_{cage} - \quad b}{\rho} \quad (8)$$

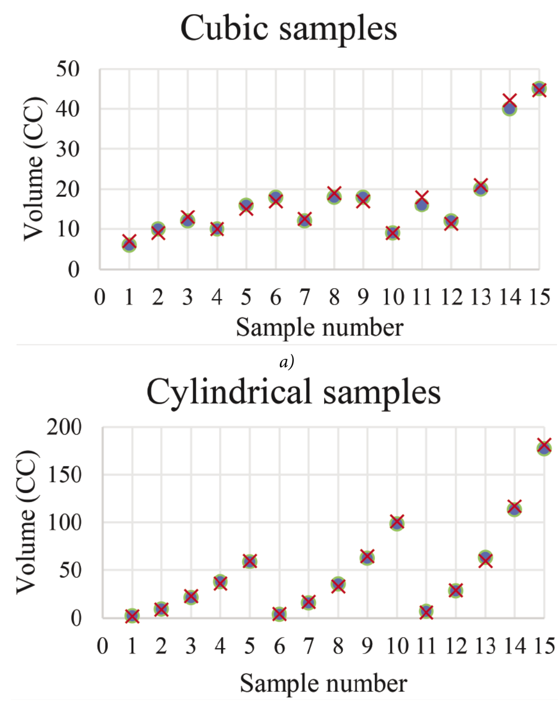
The apparent volume of foam glass is the sum of V_1 and $V_{open\text{-}porosity}$.

To check the validity of this argument, different cubic and cylindrical shapes with different dimensions were tested. The material of examined samples was made of plastic material and the samples did not absorb water. The obtained density of water was measured as 995.4 gr/lit. After the initial experiments, foam glass was made using recycled window glass and with a combination (in weight) of 1%, 2%, and 3% of silicon carbide and 1%, 2%, and 3% of alumina. In order to fabricate the samples, 4 grams of the mixture was poured into a mold with a diameter of 2.5 cm and after the cylindrical tablets were pressed, they were sintered in the furnace.

To check the density of the samples, first, their dry weight was measured, and their volume was obtained from the explained method.

3. Results and discussion

Fig. 3 show the comparison of measuring the volume of cylindrical and cubic samples by the modified Archimedes method and the geometrical measurement. As can be seen, the difference between the results of these two types of volume measurement is very small, the reason for the small difference that is observed is the measurement error. One of the most common errors can be the error in measuring the density of water. Another error is in measuring the weight of the sample because when the sample is immersed in water, the turbulence of the water can cause errors in the measurement. On the other hand, the scale used was a scale with 2 decimal digits, so it enters another error. Another error is the inaccuracy in measuring the dimensions of the samples by caliper and the asymmetry of the samples can cause errors so that there is a possibility that the examined samples are not perfectly cubic or cylindrical.



b)

Fig. 3 The difference in obtained volume from geometrically measurement and modified Archimedes measurement in cubic (a) and cylindrical samples (b) (the red marks show data for geometrical volume and the blue marks represent the Archimedes measurements)
3. ábra A geometriai mérésből és módosított Archimedes-mérésből kapott térfogat különbsége négyzetes (a) és hengeres alakú minták esetén (b) (a piros jelek a geometriai térfogatra vonatkozó adatokat, a kék jelek pedig az Archimedes mérések eredményeit jelölik)

Sample No.	Water absorption (w%)	Open porosity volume (CC)	Foam glass volume (CC)	Expansion (V%)	Density (g/CC)
1	6.605	0.258	11.950	336.081	0.326
2	15.910	0.620	19.734	555.000	0.196
3	81.268	3.173	21.053	592.088	0.184
4	15.473	0.601	14.034	394.692	0.275
5	46.433	1.803	17.171	482.895	0.225
6	8.669	0.340	15.536	436.935	0.251
7	41.645	1.630	9.788	275.279	0.398
8	7.489	0.296	10.689	300.616	0.368
9	12.784	0.503	13.369	375.988	0.292

Table 1 Extracted data from the experiments on foam glass
1. táblázat Üveghab minták esetén végzett vizsgálatok eredményei

With all the explanations that were given, the maximum error between measuring the volume through geometry and the explained modified Archimedes method is 4%.

In the test conducted on foam glass samples, the amount of water absorption, the volume of open porosity, the percentage of volumetric expansion, and the volume and density of the samples were extracted as well. The average data for each group of samples is given in the table below (*Table 1*).

According to the results, it can be concluded that the method proposed in this research is one of the simplest methods to find the density of foam glasses precisely. This method has very low error and its accuracy is high. For using this method, fluids with lower surface tension can be used in order to better saturate the foam.

4. Conclusions

In this study, a modification of the Archimedes method was presented and discussed theoretically and experimentally in order to obtain the volume of porous materials. To measure the volume of foam, the following steps should be done:

1. A cage with a higher density than water should be provided.
2. The weight of the immersed cage in water should be measured.
3. Weight of dry foam glass or other required object which is required to find the volume.
4. The foam glass should be boiled in water for 4 hours until its open pores are saturated with water.
5. The saturated foam glass should be weighed.
6. The next step is to put the saturated object in the cage and measure the weight of the set (cage and object) as it is immersed in water.
7. Finally, the apparent volume of the object could be calculated using *Eq. 5*, *7* and *8*.

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