Hygienic toilet with fast flush and low water consumption

V.V.Zhurin, L.V.Zhurin

Colorado Advanced Technology LLC

Email Address: slava_zhurin@msn.com

People spend quite a bit of time in this “sacred” and “terrible” place called a toilet, depending on health and mood. The toilet that is in our house or in public places of every industrial country was introduced only about 150 years ago. Clean normally operating toilets play very important role in our life. However, the toilet always was and still is a “weak” point in human culture.

People sense danger from toilets their everyday use at home and in public places. During toilet flushing and especially during the evacuation process toilets produce splashes, large and small, and reflections from the bowl and its walls; small droplets of liquid impregnated with evacuation particles become aerosols and spread everywhere. Splashes, reflections and aerosols spread directly to the human body opened parts such as the vaginal opening, the anus and the toilet room area. These undesirable elements of human evacuations can contain germs: bacteria and viruses that produce a substantial risk for people to become infected with all unpleasant consequences.

In this article the problem of everyday contamination caused by a toilet operation is investigated. The danger of such contamination, and what can be done to prevent contamination through a modification of existing toilet design, and how to stop a toilet phobia is discussed in detail.

The analysis and efforts on the major source of people’s possible contamination, the toilet bowl are presented; though there are other parts in toilet culture that also need attention, such as the toilet seat, utilization of clean toilet paper, thorough washing hands and other parts of human body after the evacuation process, regular air change, etc.

The invented hygienic toilet with antibacterial soap foam is described as the method for elimination of splashes and reflections during the evacuation process.

There is also presented a new approach for the utilization of water, or any other washing liquids for the toilet flushing mechanics and see what can be done for optimization of such a process, including obtaining the maximum detergency of a toilet bowl with minimum amount of water, or other washing liquid.

In general, this article is a description of new ways to improve a toilet that could be utilized by everybody without a risk being contaminated, especially those with weak immune systems, and who suffer from a toilet phobia.

Introduction

It is well-known fact that many people dislike being in and utilizing public toilets and feel a sense of danger, because toilets, as a rule, are not clean due to splashes and aerosols coming from toilet bowls and their contents. Some people, actually quite a large number of people, suffer from a so-called toilet phobia syndrome (according to BBC news of November 10, 2007, four million Britons, or 6.7% of all population suffer from a toilet phobia) and they are avoiding public toilets in a fear of being in a contaminated "dirty environment". And if one can assume that Americans have a similar attitude to a toilet, that will be about 20 million people. Let us note that this negative attitude about public toilets was not inspired by a public media, or scientific articles; people, even uneducated ones, have got this negative feeling from their own experience that can be called an everyday human experiment.

Here are several important questions. Is it necessary to change existing situation with public usage of toilets? What is the role of the toilet in transmission of certain deceases? Can we make the toilet a friendly place, return people to public toilets, and prevent a toilet phobia of many people?

The answer for the first question is obvious. We, as an advanced technological society must improve existing situation with public toilets. We cannot simply complain and increase a number of people suffering from a toilet phobia syndrome.

The role of a toilet in transmission of various deceases is discussed below in detail. And, unfortunately, a toilet represents substantial danger for many categories of people.

For the third question, the answer is that it is certainly possible to make a toilet a friendly place, and one of the possibilities to do this and prevent a toilet phobia is the hygienic high detergency toilet discussed below.

Everybody knows the situation with public toilets. Generally and mildly speaking, it is inadequate even in wealthy industrial countries [1]. Toilets are, as a rule, dirty, and most people try to avoid them, using them only because they have to, and there is no home toilet nearby. Moreover, some people are afraid of their own toilet because they clearly see that it is practically impossible to avoid germs even at home. It is obvious that clean, easily accessible toilet is an important part of a healthy society that encourages and increases business, tourism, makes citizens proud of their place and country.

With wide spread of infectious deceases one should consider at present time the toilet as a possible source of many illnesses. Human immune system of the majority of people is surprisingly strong and most of the time resists attacks from various germs. However, there are certain categories of people that have weak immune systems, such as young kids, old, and sick, and, in particular, who have problems with their immune system: HIV, AIDS, those under a chemotherapy, having transplants, and using drugs suppressing immune system. Also, in some cases, healthy people can be a target for germs, if they have cuts, bruises and "openings". In recent years there were outbreaks of very contagious deceases such as SARS, salmonella, etc that could be transmitted through a toilet.

In the last decade many countries and industries achieved substantial progress in promoting awareness to poor toilet conditions. World Toilet Organization (WTO) was established in 2001 to bring the poor situation with toilets and sanitation to general attention. WTO is a growing network of 91 member organizations from 46 countries. WTO is a global voice for addressing the global concern about toilets and sanitation problems. There are several toilet producing companies that significantly improved toilet technique and introduced various types of toilet bowls and water tanks, with good flushing ability, minimum water consumption and plurality of helpful improvements and gadgets that make our life more pleasant. However, expensive gadgets and even helpful sample analysis of human evacuations do not protect us from germs generated by a toilet operation.

1. Toilet bowl, splashes, reflections, aerosols

Let us look at general problem of interaction of evacuations with a toilet bowl water and bowl surface. In the simple case, water droplets (or any other liquid, like urine) falling on a water surface represent quite an interesting phenomenon.

During fall of a liquid droplet on a water surface, depending on a droplet's fall height and mass, it is possible to observe various liquid vortexes. Considering realistic heights experienced by human being during the evacuation process from 30-50 cm and up to 100-150 cm of liquid falls, when liquid flows, or a droplet falls on a water surface, there is developed a ring consisting of falling and moving down liquid on a water surface. Together with a vortex a certain liquid volume moves developing a vortex's body. The character of motion strongly depends on the ratio of densities of water and falling liquid (urine). In this case, differences in density in tens parts of a percent happen to be significant [2].

The mechanism of vortex development during a droplets falling can have various characters. If a liquid droplet falls from a height of 1-3 cm, then its entrance into water is not accompanied by a splash and its surface at the contact with water is deformed weakly. At the boundary between a droplet and water there is developed a rotating layer that transforms into a ring of denser liquid surrounded with water captured by a vortex.

During a droplet's fall from a larger height (over 3 cm) the mechanism of vortex development is different. Here a falling droplet, while deforming flows on a water surface, is applied at an area much larger than a droplet's diameter a momentum with a maximum intensity at a droplet's center. In result, on a water surface there is observed an expanding cavity, which then collapses developing a cumulative splash shown in Fig. 1. The mass of a splash exceeds a droplet's mass by several times.

In Fig. 1 one can see qualitatively the three successive phases of interaction of a liquid droplet falling vertically to a water surface [2]:

Phase 1: water surface is slightly bended down;

Phase 2: falling droplet is immersed into water; an air cavity is developed behind a droplet;

Phase 3: kinetic energy of falling droplet is transformed into collapse of a cavity. In result of collapse a liquid jet having a cumulative character is developed and directed into original droplet's location.

Also, in this case, if droplet, or a liquid flow is directed at a certain angle to a water surface, there is developed an oblique cumulative jet directed toward initial motion of a droplet, or a liquid flow (that effect explains why men during urination process get their legs covered with reflected liquid!).

Solid objects or liquid flows falling to a water surface produce the same effect as liquid droplets represent more complex picture in comparison with one droplet. Interaction of solid and semi-solid objects with toilet bowl walls produces complex reflections from a bowl surface due to its curvature; however, the result is very much the same as liquid interactions: substantial parts of liquid and solid evacuations go back to a user.

Splashes, which represent a sudden disturbance of a liquid's free surface, consist of a mixture of water and falling liquid and solid objects. Splashes developed in the result of interaction of falling liquid with a toilet bowl water and its surface can propagate into air in a form of liquid droplets and solid particles over 2 meters from a toilet bowl water surface. Some droplets after a flight of 1-2 meters, depending on a relative humidity of a surrounding, become evaporated and, having size from parts to hundreds of mkm (called aerosols), can float and propagate substantially longer distances. Our experiments show that such aerosol particles (from 1 to 40 mkm) can be registered at distances over 5 meters from the point of initial interaction of liquids, or solid objects with liquid.

There are several studies of falling water droplet on a water surface pictures [6] and computer simulations [7], which show similar to Fig 1 character of droplet interaction with a water surface.

2. Toilet related health problems

Aerosol particles can be described according to their physical and biological origin. Bio-aerosols include allergens, fungi, bacteria, and viruses. Fecal particles range between 10 – 40 mkm [3]. Vaporized compositions of water, urine and germs that have been generated in a toilet bowl can travel even over 5 m in a form of subparticles of 1 to 40 mkm.

In a Cooperative Canadian and American Project (CCAP) "Maximum Performance Testing of Popular Toilet Models" [4] there were tested varieties of toilets of major world toilet producing companies for toilet operations such as flush performance of human waste and water exchange. In a water exchange test there was measured a capability of toilets for removal of a brine mixture utilizing an electrical conductivity meter. About 20 ml of 18 gram/liter salt solution were added to a test bowl and dissolved. The electrical conductivity of water was measured and recorded. Then a toilet was flushed and refilled. The refilled water electrical conductivity in the test bowl was again measured and recorded. From here the percentage of water change-out was calculated. All toilets tested achieved a change-out rate of at least 98 percent. From these tests one can conclude that the remaining less than 2 percent of dissolved waste would present problems during the next toilet operation, because most people have bacteria and viruses in their waste evacuations.

According to data given in [5] the typical numbers of fecal Coliform bacteria per gram of wet human feces are 13 million. In other words, 1 percent of dissolved waste remaining in a toilet bowl after flushing would have about 130,000 bacteria per gram and some of them during the evacuation process could be spread to a toilet user in one, or another form.

There is a series of articles [8-12] that address the problem of people's possible contamination caused by utilization of toilets. The works [9-12] consider that bacteria and viruses seeded into toilets remain in the toilet for a long time after multiple flushing and even cleanings with antibacterial fluids. In some cases, salmonella bacteria after seeding survived in the toilet bowl for up to 50 days [10].

Hong Kong scientists studying outbreak of severe acute respiratory syndrome (SARS) in 2004 came to conclusion that one of the possible mechanisms of SARS transmission in several apartment buildings standing close to each other may have been spread through a flushing toilet instead of passing from person to person directly [11]. They explore the possibility of airborne aerosols as result of toilet flushing that can travel from one place to another through a ventilation system.

In two genitourinary medicine (GUM) clinics and in a leisure and fitness center investigations showed contamination of various environmental surfaces with human papillomaviruses including contamination of the clinics toilets [12].

From various publications and our research, one can consider that during toilet utilization people have quite good probabilities of contamination through several possible ways:

1. During human's evacuation process, when multiple splashes and reflections take place. Also, during contact of evacuations with a surface of water and toilet bowl walls reflected packs of water, urine and feces, and mixture of all these components there are always developed small atomized particles-aerosols that can be suspended in air and travel quite long distances.

2. In the process of water flushing with the purpose of removing human evacuations, water coming from a toilet rim in most toilets flows chaotically through multiple holes colliding with each other and with evacuations placed on a water and toilet bowl surface. Such collisions lead to multiple splashes and development of atomized particles-aerosols too.

3. A toilet seat, in most cases, is not clean and becomes contaminated during a human evacuation process. There is a series of articles, in which a toilet seat is blamed for contamination of users. Several companies developed toilet seats that are covered with a clean paper (Sani-Seats with SaniWrap Cover [22]), or can be easy removed and washed (BemisSeats [23]), and some companies make toilet seats that are automatically washed while rotating through a washing liquid (Switzerland CWS BestCleanSeat [24]).

3. Illnesses caused by a toilet usage

As it was above discussed, a toilet can be a source of various germs. Some germs die practically immediately exposed to dry atmosphere, some stay longer, but many germs in a humid air and wet areas, especially, under a toilet bowl's rim can stay and multiply extensively. And before germs expire they can be transmittable and infectious. Germs infect opened wounds on human body, wet and opened areas such as anus and vaginal.

Here are several types of illnesses that can be transmitted through the toilet:

- **SARS**, or Severe Acute Respiratory Syndrome is transmittable through toilet evacuations, aerosols, toilet seats, toilet paper that becomes impregnated with aerosols, some parts of a bathroom that can be touched by a user [11].
- **Salmonellosis** is an infection with bacteria called Salmonella causing diarrhea, fever, and abdominal cramps in 12 to 72 hours after infection [10].
- **Herpes** caused by virus called Herpes Simplex Virus (HSV) [10].
- **Papillomaviruses** is a genital HPV (Human papillomavirus) infection in men and women [12].
- **Parasites** which are Trichomonas vaginalis, Scabies, Pubic lice [10].
- **Venereal Diseases** such as Gonorrhea with gonococcus bacteria [10].

4. Financial consequences of toilet related health problems

Urinary incontinence is caused by a limited mobility (preventing timely access to a toilet) of people that are afraid of using a public toilet. According to 1996 data: 13 million Americans are incontinent; among them 11 million are women. $16.4 billion is spent every year on incontinence-related care: $11.2 billion for community-based programs and at home, and $5.2 billion in long-term care facilities. $1.1 billion is spent every year on disposable products for adults [20].

Salmonellosis. In recent years problems related to *Salmonella* have increased significantly, both in terms of incidence and severity of cases of human salmonellosis. The total cost associated with *Salmonella* is estimated at US$ 3 billion annually in the United States only [21].

Venereal Diseases are a series of diseases that are usually transmitted through sexual contact between persons, most commonly through vaginal, oral or anal sex. Toilet splashes, reflections, aerosols, and toilet seat can contaminate a toilet user with a venereal disease. Cost of venereal diseases treatment, impact on personal life is enormous.

5. Hygienic toilet with low water consumption

5.1. Toilet design without splashes and reflections

Modern physics and fluid mechanics indicate several ways for elimination of splashes during contact of liquid droplets with liquid and solid surfaces.

1. One of the recently discovered [15] methods is the utilization of comparably moderate vacuum of 223 Torr, or about 1/3 of 1 atm. Experiments made by a group of University of Chicago physicists showed that splashing can always be suppressed no matter from what initial height liquid was dropped, if the pressure is low enough (equal, or lower than 223 Torr). Unfortunately, the utilization of vacuum technique for elimination of splashes and reflections in a toilet is impractical and would be quite expensive.

2. As it was above noted, free fall of a liquid droplet from a height of 3 cm, or less produces no splashes (at such a low height there is not enough energy in a falling droplet). As one can see, a 3 cm height is also impractical.

3. Another approach is the utilization of a toilet bowl walls and a water surface covered with a substance that during a contact of water, or solid and liquid evacuations with a toilet bowl walls and water would not reflect incident particles or liquids back to a toilet user. A good candidate for such a substance is foam, and, especially, a foamy disinfecting soap and its compositions.

Foam consists of a large group of bubbles composed of a gas-liquid phase. Foam is a member of the class of materials that also known as surface-active agent that in small quantity significantly affects the system's surface characteristics. The process of foam development takes place during gas dispersion in a liquid medium and formation of a new gas-liquid phase in a form of large groups of bubbles. Creation of a stable highly dispersion foam is provided by additives of foam stabilizers or foam developers. Soap bubbles can exist due to a surface tension force. This force is caused by the attraction between molecules of a soap film. Our approach for having no reflections and splashes in a toilet relates in general to the utilization of self-foaming liquid soap compositions that provide necessary surface tension between soap bubbles and prevent bubbles from destruction for a reasonable time of about **15-20 minutes**. In particular, this approach relates to a self-foaming antibacterial soap that can cover walls and a toilet bowl surface that can protect these walls and a bowl water surface during user's evacuations. The use of foam generating equipment until recent times was a cumbersome and time consuming. However, the latest advances in development of self-foaming devices that are inexpensive and simple make this problem easy to solve.

Our research was carried out to determine: 1. a necessary thickness of self-foaming antibacterial soaps for producing stable foam of the desired properties such as density of developed foam; 2. foam's optimum thickness; 3. a drying up time of foam upper layers (that are in immediate contact with a surrounding air) that depends on air humidity, pressure, temperature and a foam chemical composition.

Foam of major U.S. liquid soap producers was utilized in the experiments with a new toilet. The characteristic feature of a liquid foam in comparison with other physical phenomena is quite a large boundary surface between gas and liquid. This surface is called lamella, which is a thin liquid film (**10-100 nm** thickness) around a gas bubble. This surface separates gas bubbles from each other. In general, any liquid is trying to achieve state where the surface energy is minimized. Since foam is in a high-energy state, one can conclude that foam exists a limited time only with foam stabilizing factors provided by most liquid self-foaming soaps.

Liquid soap viscosity gives about $\nu \approx$ **1** $\mathbf{cm^2/sec}$, so utilizing a Stokes formula, and for a bubble's radius of $\mathbf{a = 10^{-1}}$ **cm** one can find a bubble's up floating velocity is $\mathbf{v \approx 3x10^{-5}}$ **cm/sec**. In other words, foam of **1 cm** thickness can stay practically without change during $\mathbf{3x10^4}$ **sec**, or for about **8 hours**, unless the other physical processes change a bubble's shape.

The experiments with various light and moderately heavy projectiles and liquid flows imitating evacuations showed that from about a **half** and up to **one**

inch layer of a soap foam applied on toilet bowl walls and on a water surface do not produce any visible and measurable splashes and reflections from a surface covered with foam in comparison with a regular bowl and water surfaces.

Further experiments have been provided with flushing a self-foaming soap and with imitations of evacuations. There was no observable malfunctioning of evacuations flushing during the experiments. All imitation evacuations together with a self-foaming soap need just one flush of water from a water tank of a standard capacity of **1.6 gallon**. Certain additives into a liquid soap such as antibacterial liquids and fragrances would help to perform a very high quality hygienic operation of this new type of hygienic toilet.

One of the approaches for implementation of a self-foaming soap for the invented hygienic toilet is the utilization of a tank comprising of two separate compartments (**Fig. 2**): one is for a regular **1.6 gallon** water volume and another is for a smaller **0.25-0.5 gallon** volume with a liquid self-foaming soap.

Since everybody observed foam in a form of a large group of soap bubbles, which always look very fragile and easy to be destroyed, there could be a concern if foam supplied from a foam compartment will be able to move through a bowl rim, which is usually designed in a shape of a hollow toroidal space. The experiments with a soap foam motion through tubes of different diameters and lengths showed that a soap foam applied from standard liquid self-foaming soap bottles moves quite well through long tubes up to **2 m** length and **10-20 mm** in diameter without noticeable destruction of soap bubbles. The application of foam through a bowl rim also showed that a soap foam moves easily from a bowl rim into a bowl area and spreads quite uniformly over a water surface. Practical usage of a soap foam makes possible to apply a layer of foam of **0.5”-1.0”** thickness into a bowl wall and a water surface in a matter of several seconds.

Schematic picture of the hygienic toilet based on the ideas presented in this article and in a patent US 7,263,727 [18] is shown on **Fig. 2**. Here the main most important parts of the toilet are numbered as: **11** – tank with two compartments; **12** – toilet bowl; **13** – tank for water flushing; **14** –compartment for a liquid self-foaming soap; **15** – inlet orifice from water tank into a rim for water flushing **24**; **16** – inlet into a self-foaming soap rim **25**; **17** – small holes for water flushing; **18** – larger holes of a soap rim for delivery of a self-foaming soap; **19** – exit channel for evacuations; **20** – converging-expanding exit channel; **22** – push button for water flushing into a rim **24; 23** – push button for self-foaming soap application into a rim **25; 28** – push button for opening valve **27** that directs water into a foam rim **25** for its cleaning, if necessary. Also in **Fig. 2** there are shown the following designations used in a hygienic toilet description and equations presented in the next chapters for a water flow through small holes and a vortex flow in a toilet bowl that is considered as a vortex chamber: $\mathbf{R_{in}}$ is a radius of a bowl rim internal side where water enters from a water tank through holes of a radius $\mathbf{r_{in}}$; $\mathbf{r_n}$ is a radius of a bowl converging expanding channel serving as a bowl's exit outlet in a narrow cross section of this channel; $\mathbf{r_v}$ is a vortex radius in a bowl's liquid flow.

5.2. Toilet bowl flushing optimization

According to the above mentioned Cooperative Canadian and American Project (CCAP) [4] a large number of toilets from major toilet makers were tested for the ability of a toilet to completely remove 100 percent of waste (performance benchmark adopted was 250 grams) in a single flush without plugging or clogging. And this, as it is stated in CCAP, was considered by most consumers and users to be one of the most important performance criteria for a toilet.

However, we believe that toilets should be also tested for another specific quality of a toilet operation: a flush with minimum of splashes, and a flush that can wash toilet bowl walls with a high efficiency.

In a toilet, a flushed water flows out of a toilet bowl rim through a series of small holes. These holes are placed in the underside of a toilet rim, around the circumference of the bowl. Incoming water from a water tank or from any other water volume flows down into the toilet rim entrance and through these holes providing a rinse effect, or "rim wash" over the entire inner surface of the bowl and also serving for removal of evacuations. That is the purpose of these holes.

However, our analysis of many toilets with gravitation water tanks and a water flow through these holes shows that, in many cases, a water flow in vicinity of holes is not evenly distributed. Only at about a half of a bowl's height down from the rim separate flows combine into one vortex flow. This means that the bowl's upper half is not thoroughly washed, and, in particular, there is always a "dead" space between separate flows supplied by each hole, and between the holes. Taking into account a water flow through bowl rim holes, a water velocity through these holes will be higher than a water velocity caused by a water fall through inlet orifice rim in several times due to the mass flow conservation law: □ **=** $\rho vS = \rho v_r n S_r$, where □ is a liquid's mass flow, **v** is a water velocity caused by a water fall at inlet orifice rim with area **S**; v_r is a water velocity at exit of a bowl's rim hole; S_r is area of one hole in a bowl's rim; **n** is a number of holes.

Since every rim of most existing toilets has about **26-32 holes**, a water velocity will be increased about proportionally to S/nS_r, or, in this case, by about **2.7 times** for $r_{in,orifice} = 2.5$ **cm** and $r_{in,hole} = 0.3$ **cm**, or a velocity of water through the holes (**26** holes rim) with $r_{in,hole} = 0.3$ **cm** will be about **8.3 m/s**, because a total area of bowl holes is smaller than area of an inlet orifice. However, for $r_{in,hole} = 0.2$ **cm** (through **26** holes rim) an exit velocity will be **18.6 m/s**. For more efficient toilet bowl washing it is possible to have **52** holes (or more) with smaller area, and one still can have a water higher velocity from these holes of about **9.3 m/s**. Further reduction of hole's area to $r_{in,hole} = 0.15$ **cm** can give about **16.6 m/s** for **52** holes.

In principle, the smaller a hole, the higher a water velocity at a hole's exit. Dimension of bowl rim holes is determined by the facts that with a hole diameter less than **0.5 mm** a carrying capacity of a hole becomes reduced due to increasing role of friction and water surface tension. And, since water contains certain impurities and salts, small holes can be clogged with depositions from impurities and salts. [*It is worth to mention that many recently popular shower heads have holes for water of a diameter of about **1 mm** and less, about **0.2 mm**; these holes sometime called micro-nozzles.]

Another important aspect in designing toilet bowl holes is an optimum number of such holes. *We recommend placing rim holes with a distance equal to at least two diameters of a hole from each other*. As our experiments showed, during a water flow through a hole there is realized a water flow swirling effect, which diameter is achieved two diameters of a hole. In a standard toilet size of a bowl's diameter of about **30-32 cm** (can be elongated such as **28 cm x 32 cm**) instead of **26** holes with $\mathbf{r_{in,hole} = 0.3\ cm}$ one can have **52** holes (or more) with $\mathbf{r_{in,hole} = 0.15\ cm}$ with substantially better washing effect and higher velocity of water flow.

In order to provide optimum transformation of water (or any other cleaning fluid) into one swirling vortex flow in a toilet bowl from the bowl rim holes it is necessary to make the holes exits with a flow direction at angle of about **45°** along a bowl's surface.

Instead of a gravity water tank one could utilize water from service pipes supplied by U.S. municipal governments with pressure of about **60 psi** (or about **4 atm**). This can be compared with the water that is applied from a water tank from a height of about **H ≈ 42 meters** (and in a regular gravity water tank this height is only about **H ≈ 0.5 m**). These estimations show that water utilization from the pressurized service water supplied to our houses would do much better job in terms of water detergency efficiency than the regular gravity water tanks. However, many homes cannot afford to have the pressure assisted water flush, and *we recommend toilets with larger number of rim holes of smaller diameter*.

5.3. Optimization of bowl geometry for fast water motion

Another way of making a toilet with enhanced hygienic qualities is to improve the efficiency of water detergency during water flushing through utilization of specially designed geometry of a bowl exit outlet for evacuations. With the latest trends to water conservation and accepting substantial limitations on utilization of not more than **1.6 gallon** of flushing water the available detergency efficiency is reduced significantly. The water action time became much shorter with less water mass flow than it was with **5.5** and **3.5 gallons** of previous standards. However, there is the way to improve the water detergency efficiency by forcing a flushing water to flow faster over a bowl surface with a high velocity vortex flow.

Our estimation of obtaining an optimum efficiency of water detergency shows that in order to utilize a vortex flow providing high detergency there are certain hydrodynamic phenomena and geometrical factors that must be applied to a bowl design. Our analysis [18] is based on application of the "shallow water" theory and the gas-hydraulic analogy introduced by N.E. Zhukovski [16].

The analogy to behavior of a compressible gas represents a motion of incompressible liquid with a free surface in a gravity field, if a depth of a liquid's layer is sufficiently small. The liquid depth must be small in comparison with the characteristic dimensions of a problem, for example, in comparison with the dimensions of uneven parts of a reservoir (toilet bowl) where liquid flows. In such a case, a transversal component of a liquid velocity can be neglected in comparison with a longitudinal component, and a longitudinal velocity can be considered as a constant value along a layer's thickness. In this so-called hydraulic approximation, a liquid can be considered as a "two-dimensional" medium possessing in every point a definite velocity **V**, and also can be characterized by a layer's thickness **h**.

Euler's general equations of motion provide a solution for the long gravitation waves that represent small disturbances of motion for a considered system. The results [17] show that such disturbances propagate in a liquid with a thickness layer **h** with a finite velocity of long waves $\mathbf{C_\lambda}$ that is equal to

$$\mathbf{C_\lambda = (gh)^{1/2},} \qquad \mathbf{(1)}$$

where **g** is an Earth gravity acceleration. In the field of inertia forces of rotating liquid with development of a gas vortex (in the case of high velocity liquid rotation, a liquid layer on a toilet bowl walls is quite small, millimeters) on a channel's axis, the propagation of long waves $\mathbf{C_\lambda}$ is equal:

$$\mathbf{C_\lambda = (jh)^{1/2},} \qquad \mathbf{(2)}$$

where $\mathbf{j = V_\varphi^2/r_v}$ is a tangential acceleration of rotating liquid, $\mathbf{V_\varphi}$ is a tangential liquid velocity on a vortex surface, $\mathbf{r_v}$ is the radius of the gas vortex.

This velocity $\mathbf{C_\lambda}$ plays role similar to a sound velocity in gasdynamics. It is necessary to note that, if liquid moves with velocities $\mathbf{V < C_\lambda}$ (quiet flow), the influence of disturbances propagates to the entire flow, down and up of a flow. If liquid moves with a velocity $\mathbf{V > C_\lambda}$ (fast, or "supersonic" flow), then the influence of disturbances propagates only on certain regions down a flow.

The ratio $\mathbf{V_x/C_\lambda = M^* = 1}$, where **M*** is an analogue of the Mach number **M** in gas. Just as the **M** number serves as a similarity criterion for gas flows, the **M*** is an analogous similarity criterion for liquid flows of a small depth.

In our research, the theory of a "shallow water" and the gas-hydraulic analogy [16] are utilized for the description of behavior of a liquid motion in channels with a variable area of a constant depth in a gravitational field. This approach is modified for the case of a fast rotating liquid (water) flow with a vortex having water and a waste through a channel in a shape of a converging-expanding channel (equivalent to a nozzle) that carries water and waste into a drainage channel.

Detailed analysis and application of the theory of "shallow water" and the gas-hydraulic analogy for design and operation of a new improved toilet are presented in our US patent US 7,263,727 "Hygienic High Detergency Toilet" [18].

In [18] it is shown that rotating water, or any other washing liquid flow with a vortex in a toilet bowl with an exit part that is in the form of a converging-expanding channel can be characterized by the geometrical parameter **A**:

$$\mathbf{A = R_{in} r_n / n r_{in}^2} \; . \qquad \mathbf{(3)}$$

where $\mathbf{R_{in}}$ (see **Fig. 2**) is a radius of a bowl's internal side where water enters from a water tank through a large inlet orifice and a toroidal rim and goes through outlet orifices of a radius $\mathbf{r_{in}}$; $\mathbf{r_n}$ is a radius of a narrow part of exit converging-expanding channel of a toilet bowl; **n** is a number of outlet orifices-holes in a toroidal rim of a toilet bowl (vortex chamber).

For a non-circular vortex chamber (elongated toilet bowl) with liquid mass flows entering through outlet orifices-holes of a toroidal rim along the chamber external side wall, the geometrical characteristic of the vortex chamber can be **A** is expressed as:

$$\mathbf{A = R_{in} r_n \pi \cos\theta/(nS_r),} \qquad \mathbf{(4)}$$

where **n** is the number of outlet orifices-holes, $\mathbf{S_r}$ is the surface area of an outlet orifice, θ is the angle between a normal vector to the vortex chamber axis. For practical estimations one should use a real number of holes in a bowl rim that is usually has about **26-32** holes (this number varies in different models, which have in general more than **16** holes).

The geometrical characteristic **A** is the similarity criterion for the devices with rotating liquid and with development of air vortex in a liquid. For different dimensions of $\mathbf{R_{in}}$, $\mathbf{r_n}$, and $\mathbf{r_{in}}$ liquid flows are similar at equal values of **A.** Also, for different values of the geometrical characteristic **A** [18] one can determine a radius of air vortex $\mathbf{r_v}$ at $\mathbf{V_x \geq C_\lambda}$, and $\mathbf{A \geq 2}$ corresponding to the critical regime:

$$\mathbf{r_{vcr}^2 = r_n^2[1 - (1/2A)^{2/3}].} \qquad \mathbf{(5)}$$

[Note. People watching how water is moving in a toilet bowl noticed that water rotates and develops what is called a water vortex, and an air vortex, which looks like a hollow space surrounded by a rotating water, $\mathbf{r_v}$, as discussed above, is air vortex radius, which is $\mathbf{r_v = r_n + h}$, where $\mathbf{r_n}$ is a radius of a narrow part of a converging-expanding exit channel, and **h** is a thickness of a rotating water layer.]

The regime of a critical and supercritical flow in a converging-expanding channel is realized for the geometrical characteristic $\mathbf{A \geq 2}$ $\mathbf{(M^* \geq 1)}$. It requires observance of the definite conditions for liquid flow from a vortex chamber (bowl space) into a converging-expanding channel. Exit of a liquid flow with evacuations through long converging-expanding channels leads to development of pressure waves in such channels. This phenomenon is similar to appearance of shock waves that occur when gases are expelled from a nozzle of a liquid-propellant rocket. Transitions from supercritical to undercritical regime of flow in long channels are caused by flow discontinuities arising from friction [18].

In a supercritical regime, liquid moves with a “supersonic” velocity $\mathbf{V > C_\lambda}$, then the influence of disturbances propagates only on certain regions down a flow, and, in general the disturbances can be mostly eliminated [18].

In our experiments, for a practical case, the following parameters of a toilet bowl that is considered as a vortex device (we did experiments with a standard toilet bowls of one of major toilet makers) were utilized: **R_{in} = 17 cm, r_{in} = 0.3 cm, n = 26** (number of holes in a bowl rim), **r_n = 3.0 cm, A = 21.8, V_{in} = 10 m/s, r_v = 2.9 cm, h = 0.1 cm, V_x = 39 m/s, C_λ = 10.98 m/s, M* = 3.55.** A mass flow for liquid (water) □$_{in}$ is varied from **6 kg/s** to **20 kg/s** (meaning that **1.6 gallon ≈ 6 *l* = 6 kg** will be released from **1** to **0.3 seconds** depending on what kind of a flushing mechanism is utilized, whether it is a regular gravity water tank, or a pressure induced flushing)**.**

For other toilet bowls, the bowl parameters could be slightly different from the above presented, depending on bowl dimensions, number of holes in a bowl rim, a hole diameter and on a water mass flow. However, the results will be about the same order of values. Note that for the above practical case with **r_n = 3.0 cm** and **r_v = 2.9 cm, h = 0.1 cm**, it means that liquid (water) flows in a thin layer of **h = 0.1 cm** with a quite fast velocity **V_x = 39 m/s**. In such a case, the detergency efficiency will be increased significantly in comparison with a regular channel. Also a liquid dynamic pressure of such a flow will be about **80 atm**.

For liquid mixtures with high percentage of a heavy component such as solid evacuations (usually about **15-20%** depending on a ratio of solid evacuations mass flow to a flushed water mass flow) it is necessary to include a correction factor into the geometrical parameter **A.**

It also follows that for each vortex chamber (various bowl dimensions) geometrical characteristic **A** there is a certain value of a critical cross section of a liquid flow (a critical depth **h_{cr}**), at which the transition to a supercritical regime of flow is realized. From the nozzle theory, it is known that *the critical and supercritical flows correspond to the maximum liquid mass flow through a converging-expanding channel* [12]. And, *liquid that flows with the maximum liquid mass flows in general practically has no splashes, providing smooth flows*.

Research with various vortex chambers and with the non-dimensional geometrical parameter **A** showed that a *significant influence of centrifugal forces*, due to the sticking and wetting nature of liquids, *allows a liquid flow* (water flow from a bowl during flushing process usually is turned at certain angle after a channel's exit) in a channel with a converging-expanding area *to turn at a high angle and avoid atomizing spray effect.*

The absence of atomizing effect is very important feature for safe (in a hygienic sense) operation of toilets because a liquid's atomizing can spread undesirable remains from evacuations and generate aerosols from evacuations and water. Instead, for a changing geometry of a bowl with a converging-expanding channel, which is an exit outlet for evacuations, it is possible to create a smooth liquid flow from a converging-expanding channel with very high velocities; for most practical cases, $\mathbf{V_{in}}$ is **10-20 m/s,** and with a utilization of a service water pipe with water pressure of about **60 psi (≈ 4 atm)**, $\mathbf{V_{in}}$ with about **52** rim's holes of smaller diameter **0.3 cm** can be over **100 m/sec**.

8. General conclusions

Here are the main conclusions from our analysis of the toilet problem, the design of a hygienic toilet with fast rotating flushing water, and what needs to be done to improve the situation with toilets:

- Existing toilets present substantial danger to health of people due to possible contamination caused by toilet operation.
- For all toilet users, and especially for those with weak immune systems, we recommend the hygienic toilet based on the ideas described in our patent [18]. This hygienic toilet has the following important features:
    - During a toilet utilization a toilet bowl surface is covered with a substance, which is a self-foaming antibacterial soap, that absorbs human evacuations without splashes and reflections back to a user.
    - Flushing water, or any other liquid moves from a bowl rim holes with a high velocity developing a vortex flow providing maximum washing quality of a toilet bowl surface and removal of evacuations.
    - Flushed *water moves* in a converging-expanding bowl's exit channel *with a supersonic speed of surface waves* without atomizing liquid.

- The *toilet design* and operation described above *provides* the best *washing effect with low noise and with minimum of consumed water*.
- It is possible to provide people with a hygienic toilet that possesses the necessary qualities of being clean, not being contaminating during the evacuation process, and at the same time being a low water consuming device. Small changes in a regular toilet are necessary to fulfill these tasks. These changes are not drastic, but the results would be very rewarding in preventing various contagious diseases, toilet phobia and making a toilet a friendly germ-free device that people would not fear.

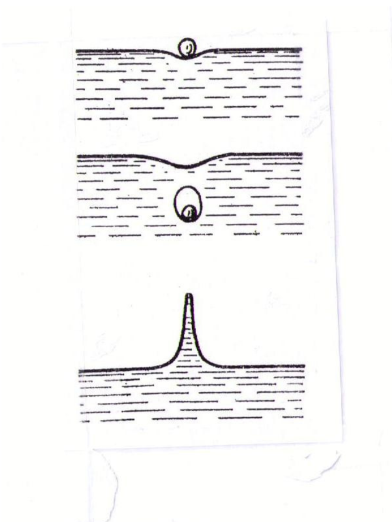

Fig. 1

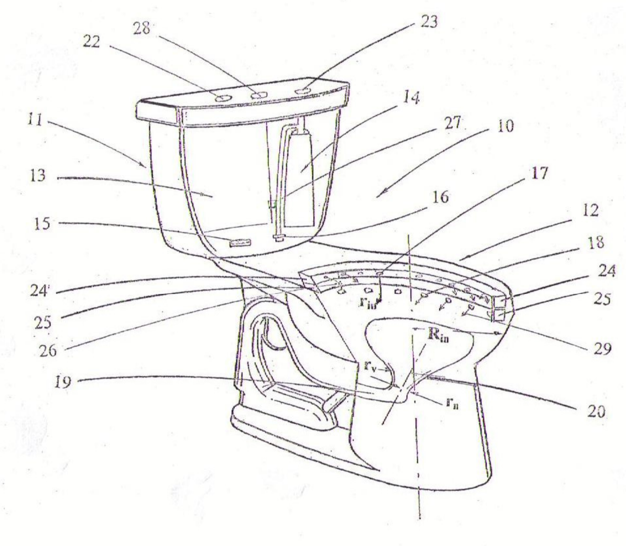

Fig. 2

References

1. C.Greed, “The role of the public toilet: pathogen transmitter or health facilitator?”, Building Serv. Eng. Res. Technol. 27, 2, 2006, pp 1-13.

2. M.A.Lavrentiev, B.V.Shabat, “Problems of Hydrodynamics and Their Mathematical Models”, Nauka, Moscow, 1973, p 291 (in Russian).

3. Platts-Mills, T. A. E., Ward, G. W., Sporik, R., Gelber, L. E., Champman, M. D., Heymann, P. W. “Epidemiology of the relationship between exposure to indoor allergens and asthma.” International Archives of Allergy and Applied Immunology 87(2), pp 505-510, 1991.

4. W.Gauley and J.Koeller, Cooperative Canadian and American Project “Maximum Performance Testing of Popular Toilet Models”, Final Report, December 2003.

5. www.oasisdesign.net

6. http://www.hiviz.com/splashes

7. S. Butson, C. Hadley, S. Pratt, D. Winters, A Systematic Study of Splashes December 5, 2000, North Carolina School of Science and Mathematics

8. C P. Gerba, C. Wallis, J. L. Melnick, “Microbiological Hazards of Household Toilets: Droplet Production and the Fate of Residual Organisms, Microbiological Hazards of Household Toilets: Droplet Production and the Fate of Residual Organisms”, MICROBIOLOGY, Aug. 1975, Vol. 30, No. 2, pp 229-237.

9. J. Barker and M.V. Jones, “The potential spread of infection caused by aerosol contamination of surfaces after flushing a domestic toilet”, Journal of Applied Microbiology 2005, 99, pp 339–347.

10. J. Barker, S.F. Bloomfield, “Survival of Salmonella in bathrooms and toilets in domestic homes following salmonellosis”, Journal of Applied Microbiology, v 89, No 1, July 2000, pp 137-144.

11. Ignatius T.S. Yu, M.B., B.S., M.P.H., Yuguo Li, Ph.D., Tze Wai Wong, M.B., B.S., Wilson Tam, M.Phil., Andy T. Chan, Ph.D., Joseph H.W. Lee, Ph.D., Dennis Y.C. Leung, Ph.D., and Tommy Ho, B.Sc., “Evidence of Airborne

Transmission of the Severe Acute Respiratory Syndrome Virus", The New England Journal of Medicine, **V** 350, No 17, p. 1731-1739, 2004.
12. S. Strauss, P. Sastry, C. Sonnex, S. Edwards and J. Gray, "Contamination of environmental surfaces by genital human papillomaviruses", Sexually Transmitted Infections, 2002; No **78**, pp. 135-138.
13. *Overview:* Urinary Incontinence in Adults, Clinical Practice Guideline Update. Agency for Health Care Policy and Research, Rockville, MD. March 1996. http://www.ahrq.gov/clinic/uiovervw.htm
14. World Health Organization. Fact sheet N°139, Revised April 2005
15. "Drop Splashing on a Dry Smooth Surface," Lei Xu, Wendy W. Zhang, and Sidney R. Nagel, *Phys. Rev. Lett.* **94**, 184-505, 2005.
16. N.E. Zhukovski, "Analogy between motion of liquid in a narrow channel and gas motion in a tube with a high speed" published in a "Collection of N.E. Zhukovski Works", v. 7, by All-Union Scientific-Technical Publishing, Moscow, 1937 (in Russian).
17. L.D. Landau and E.M. Lifshits, Theoretical Physics, v. VI, "Hydrodynamics" "Nauka", Publishing House of Physical-Mathematical Literature, Moscow, 1986.
18. V.Zhurin, L.Zhurin, US patent No 7,263,727 "Hygienic High Detergency Toilet".
19. J.R.Kanicky et al, "Cooperativity Among Molecules at Interfaces in Relation to Various Technological Processes: Effect of Chain Length on the pK_a of Fatty Acid Salt Solutions", Langmuir Journal, **16** (1), pp 172-177, 2000.
20. *Overview:* Urinary Incontinence in Adults, Clinical Practice Guideline Update. Agency for Health Care Policy and Research, Rockville, MD. March 1996. http://www.ahrq.gov/clinic/uiovervw.htm.
21. World Health Organization. Fact sheet N°139, Revised April 2005.
22. http://www.cleanseats.com.au .
23. http://www.bemismfg.com .
24. www.cws.com .