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Introducing a Promising New Disinfection Technology for the Fonce River in Colombia

Presentación de una nueva y prometedora tecnología de desinfección para el río Fonce en Colombia

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Abstract

Urban wastewater disinfection is a critical component of environmental sustainability and human health. Current technologies for this are often costly and inaccessible to many communities. Typically, this treatment is carried out by chemical processes, with chlorination being the most common despite the potential for harmful disinfection byproducts. However, the emergence of promising alternatives, such as physical processes that utilize hydrodynamic cavitation reactors (HCRs), offers significant energy and environmental benefits. Based on this, the Fundación Universitaria San Gil, UNISANGIL, has developed a technology that utilizes hydrodynamic cavitation (HC) to disinfect urban wastewater samples discharged into the Fonce river in San Gil, Santander, Colombia. The primary objective of this research was to test the ability of a hydrodynamic cavitation system to reduce total coliforms and fecal coliforms (*E. coli*) in a 200 L tank containing 12.5 L of domestic urban wastewater diluted in 187.5 L of non-residual water. The methodology consisted of three steps: HCR design and simulation, HC implementation, and disinfection measurement. The experiments were conducted with a Venturi-type HCR, designed with computational fluid dynamics, and tested with wastewater samples from one of the ten discharges that flow into the river. The results obtained for a system with a flow capacity of 0.00625 m^3/s show an average growth inhibition rate of 31.72 %, 59.45 %, and 84.53 % for one, ten, and twenty water recirculation, respectively, with an energy efficiency of 2327.6 CFU/J. The highest results reach a Growth Inhibition Rate (GIR) of 93.40 %, a Logarithmic Reduction (LR) of 1.18 for Total Coliforms, and a GIR of 95.12 % and an LR of 1.31 for *E. coli*. Finally, it is concluded that this technology holds great promise for efficiency and operational viability, with further testing required to realize its potential.

Keywords

Wastewater treatment, wastewater disinfection, hydrodynamic cavitation, hydrodynamic cavitation reactor, computational fluid dynamics.

Resumen

La desinfección de aguas residuales urbanas es un componente crítico de la sostenibilidad medioambiental y la salud humana. Las tecnologías actuales suelen ser costosas e inaccesibles para muchas comunidades. Normalmente, este tratamiento se realiza mediante procesos químicos, siendo la cloración el más común a pesar del potencial de subproductos nocivos. Sin embargo, alternativas prometedoras, como los procesos físicos que utilizan reactores de cavitación hidrodinámica (HCR), ofrecen importantes ventajas energéticas y medioambientales. Sobre esta base, la Fundación Universitaria de San Gil, UNISANGIL, ha desarrollado una tecnología que aprovecha la cavitación hidrodinámica (HC, por sus siglas en inglés) para desinfectar muestras de aguas residuales urbanas vertidas al río Fonce en San Gil, Santander, Colombia. El objetivo principal de esta investigación fue probar la capacidad de un sistema de cavitación hidrodinámica para reducir coliformes totales y fecales (*E. coli*) en un tanque de 200 L que contenía 12.5 L de aguas residuales urbanas domésticas diluidas en 187.5 L de agua no residual. La metodología constó de tres pasos: diseño y simulación del HCR, montaje del HC y medición de la desinfección. Los experimentos se realizaron con un HCR de tipo Venturi, diseñado con fluidodinámica computacional, y se ensayaron con muestras de aguas residuales de uno de los diez vertimientos que desembocan en el río. Los resultados obtenidos para un sistema con caudal de 0.00625 m^3/s muestran tasas medias de inhibición del crecimiento del 31.72 %, 59.45 %, y 84.53 % para una, diez y veinte recirculaciones de agua, respectivamente, con una eficiencia energética de 2327.6 CFU/J. Los resultados más elevados alcanzaron una tasa de inhibición de crecimiento (GIR, por sus siglas en inglés) del 93.40 % y una reducción logarítmica (LR, por sus siglas en inglés) de 1.18 para Coliformes Totales, y un GIR del 95.12 % y un LR de 1.31 para *E. coli*. Se concluye que esta tecnología es prometedora en cuanto a eficacia y viabilidad operativa, siendo necesarias más pruebas para potenciar su uso.

Palabras clave

Tratamiento de aguas residuales, desinfección de aguas residuales, cavitación hidrodinámica, reactor de cavitación hidrodinámica, fluidodinámica computacional.

1. INTRODUCTION

Urban wastewater is a critical problem at a global level due to the significant impacts it produces on the environment and human health. These waters come from various human activities in urban areas, such as households, industries, and commercial establishments, and often contain a wide range of physical, chemical, and biological contaminants [1]. According to estimates from the United Nations (UN), only around 20 % of the world's wastewater receives some treatment before being discharged into the environment [2], which causes the contamination of freshwater bodies, soils, and aquifers and affects biodiversity, also promoting the spread of infectious diseases.

Urban wastewater treatment can help mitigate these problems. Modern wastewater treatment technologies seek to remove diverse contaminants, from solids and nutrients to pathogens and toxic chemicals [3]. However, the available technologies must still be more affordable to all communities, especially in developing countries [1]. Despite technological advances, there are still challenges in urban wastewater treatment, such as managing the waste generated during treatment and eliminating emerging contaminants, such as pharmaceuticals and microplastics [4].

The different disinfection methods are currently classified into two main categories: physical and chemical. Chemical disinfection methods use chemicals to kill or inactivate pathogens. Chlorine is the most widely used disinfectant due to its effectiveness, low cost, and the possibility of providing residual protection [5], [6]. However, chlorination can also produce potentially harmful disinfection by-products, like trihalomethanes[7], and there are chlorine-resistant bacteria, which has motivated the exploration of alternatives such as ozone and chlorine dioxide [8]. Ozone is a powerful oxidant that can quickly inactivate many microorganisms, and chlorine dioxide is particularly effective against viruses. Nevertheless, ozone is not used for continued disinfection. Hence, research focuses on combining methods that, however, could generate toxic oxidation by-products, too, due to the interaction of oxidants and dissolved organic matter [9].

Traditional physical disinfection methods include ultraviolet (UV) radiation, heat, and filtration. Research on UV disinfection is of particular interest because it is based on the ability of UV radiation to damage the DNA of microorganisms, which inhibits their ability to reproduce and cause infection [10], [11]. However, some microorganisms may survive it, and UV treatment is unsuitable for continuous work. One alternative to traditional physical methods and chemical methods is using hydrodynamic cavitation reactors (HCR), which, according to [12], are efficient and promising given the energy and environmental benefits they imply. Hydrodynamic cavitation (HC) is a topic of growing scientific interest, along with its application for wastewater treatment, as evidenced by the number of publications associated with the topic in the last 20 years (see Figure 1).

Several works, for more than two decades, have laid the foundations of the scientific and technological basis of HC. Reviewing this pioneer publication is essential to understanding the fundamentals of this technology and inferring its actual possibilities. For example, research by [13] described the fundamental design elements for constructing hydrodynamic cavitation reactors, the so-called cavitation number (σ_v), and the mathematical model of turbulence and cavitation dynamics. In [14], the main applications of cavitation are disclosed, and the most common cavitation techniques (hydrodynamic, acoustic, optical, and particle) are presented, as well as the main configurations of the reactors.

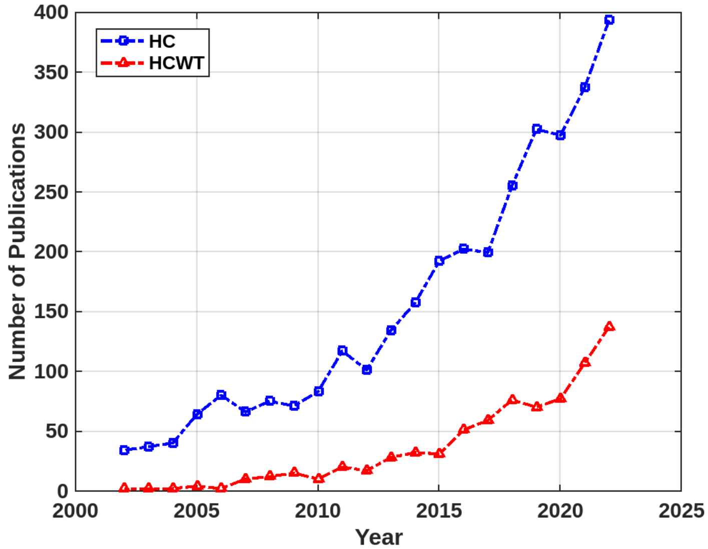

Figure 1. Publications on Hydrodynamic Cavitation (HC) and HC Wastewater Treatment (HCWT), reported by SCOPUS. Source: created by the authors.

For its part, [15] offers a theoretical study of hydrodynamic cavitation as an advanced oxidation process. The authors analyze the parameters they believe should be considered (time scales, compression periods), highlighting its greater energy efficiency than other techniques. A complete synthesis of the operating principle and the main applications of HC, both in physical and chemical processes, is structured in [16], where two design alternatives are explored (orifice plate and Venturi tube), together with their most relevant parameters (perimeter and area ratio, opening angles, among others), underlining that the optimal operating point depends to a great extent on the application for which the cavitation system is used, so that, for example, for the disinfection of wastewater, a greater affectation of the cell wall of the microorganisms occurs for a smaller cavitation number concerning the perimeters of the water passage areas, so it is concluded that the geometry of the cavitation system, the inlet pressure and the cavitation number (σ_v), control the alteration of microbial cells.

Within the applications of HC, studies focused on treating wastewater (removal of contaminants) and its disinfection (reduction of pathogenic microorganisms) stand out. Reference [17], presented the results of the combined use of HC and H_2O_2, as well as HC and Ozone, for the degradation of a cationic dye (Rhodamine 6G). The best results were obtained for the combination of HC and ozone, reaching a decolorization of up to 100 % and a TOC (Total Organic Carbon) reduction of up to 73.19 %. The research in [18], reports the degradation of tetracycline using the combined management of hydrodynamic cavitation and photocatalysis, evidencing that alkaline pH values favor degradation. For a pressure of 0.34 MPa and a flow of 105.7 mL/s, the work estimated a σ_v of 0.59 using a circular Venturi cavitation system. Subsequently, a review of works focused on the treatment of wastewater by cavitation-based oxidation methods is presented in [19], where research on acoustic and hydrodynamic cavitation is analyzed, in combination with alternative techniques such as the Fenton process, ozonation, use of H_2O_2, UV, among others. The study also elaborates an economic analysis of the implementation of cavitation techniques, highlighting HC as the one with the lowest cost and the most excellent ease of scalability. Other works that explore the use of HC for the removal of contaminants are [20]-[23].

Specifically, in water disinfection, a pioneering work is [24], which explores ozone-based disinfection combined with HC. This method reduced total coliforms, fecal coliforms, and fecal streptococci. The authors show that this type of hybrid disinfection is more energy efficient. The work of [25] analyzes the use of cavitation reactors for wastewater disinfection. The text analyzes chemical acoustic and hydrodynamic cavitation systems, detailing the main parameters that must be considered for proper operation (for example, the diameter of the tubes in a Venturi-type cavitation reactor or the ratio between the free area for the flow and the area of the pipe). The article also explores the requirements for future research regarding industrial implementation. The studies of [26] expose hydrodynamic cavitation for wastewater treatment, particularly for removing pharmaceutical residues, bacteria, microalgae, and viruses. Three configurations for hydrodynamic cavitation were experimented with HC by cycles, continuous HC, and HC by shear. In all experiments, the maximum possible flows and pressures were sought. In continuous HC, super cavitation was achieved with a cavitation number σ_v of 0.75 and a flow velocity of 6.7 m/s. For HC by shear, velocities of up to 26 m/s were reached. In removing bacteria (L. pneumophila), continuous HC with and without supercavitation was used, with better results achieved for HC with supercavitation. The removal of bacteria M. aeruginosa and C. vulgaris was also experimented with, using the growth inhibition rate as a metric. It was found that there was no removal for C. vulgaris, while for M. aeruginosa, the removal reached 90 % four days after treatment.

Another important work is that of [27], which identifies the dimensionless parameters that control the disinfection efficiency in classical HCRs, such as orifice plates. It shows a new set of experiments designed to isolate, primarily, the effects of the cavitation number (σ_v). This work establishes that the disinfection efficiency of orifice plates increases as the value of σ_v decreases and that the initial concentration of bacteria (C_0) does not have an apparent effect on the disinfection efficiency, findings that, however, require further research and standardization. A study highlighting the usefulness of hydrodynamic cavitation for water disinfection is the work of [28]. This study discusses the conditions necessary for operation in environments out of the laboratory and aspects related to the design of cavitation reactors. The authors also agree on the greater economic and logistical feasibility of hydrodynamic cavitation processes compared to acoustic cavitation for applications in natural environments and the improvements brought to the process by combining hydrodynamic cavitation with advanced oxidation techniques. Two thorough reviews of research results aimed at the study of disinfection of water contaminated with microorganisms and detailing, in most cases, results for *E. coli* analysis are those carried out by [29] and [30]. These authors summarize the results of disinfection processes carried out with different types of reactors, showing disinfection rates close to 100 % in most cases. However, these works are generally developed in laboratory environments, in which distilled water is tested with the microorganisms to be treated, having been previously incubated in a regulated manner. In this same sense, the work of [31], with a vortex diode reactor, that of [32], which uses a mixed technique with a vortex diode reactor complemented with an injection of natural oils, and that of [33] with a rotary reactor, are presented.

Although fewer in number, there are also works related to the disinfection of natural sources contaminated by humans, such as that of [34], in which water samples from Lake Brno in the Czech Republic were treated in the laboratory by combining hydrodynamic cavitation and H_2O_2, in order to inhibit the photosynthesis of cyanobacteria, achieving inhibition rates of 60 % and continuous reduction of colonies. In a similar line is presented the work of [35], in which microorganisms present in water samples from Padmakshi Lake, in Warangal, Telangana State, India, a lake contaminated with domestic wastewater, were reduced. The study presented reductions of COD and BOD of water treated with hydrodynamic cavitation and H_2O_2 of 64 % and reported a reduction of more than 95 % of microorganisms without specifying their type. Other works on the use of HC for water disinfection are[36]-[38].

These studies demonstrate the relevance of hydrodynamic cavitation as an alternative method for water disinfection, but at the same time, reflect the need for further studies with water from natural environments. With a base on these studies and considering the necessity of more process of research and development in treatment and disinfection systems for wastewater, that possibilities the implementation of more efficient, accessible, and sustainable solutions that generate data and decision-making elements for new technologies and technological developments prior to investment stages related to technological readiness levels (TRLs) greater than 4, the Fundación Universitaria San Gil - UNISANGIL has developed a novel disinfection technology using an HCR. This technology, which has been tested with wastewater from one of the ten discharges that fall on the important Fonce river in San Gil, Santander, Colombia, is a significant departure from traditional methods and has shown promising results in reducing the percentage of disinfection of fecal coliforms (*E. coli*) and total coliforms in samples of domestic residential water. The Fonce river is crucial for the economic development of 70.000 people in the south of Santander department of Colombia. The present work represents a significant and fundamental contribution to world research on the subject since it deals with the reduction of microorganisms in water samples collected directly from a natural discharge into a river, as well as the volume of treated water (200 L).

This paper presents the results of our research, detailing the materials and methodology used, the main results obtained, and the conclusions confirming the viability of the technology tested. The promising results of our research point to the potential of this technology to revolutionize water disinfection, offering hope for a more sustainable and accessible future.

2. METHODOLOGY

The methodology was executed in three phases, according to the scheme shown in the following figure (see Figure 2).

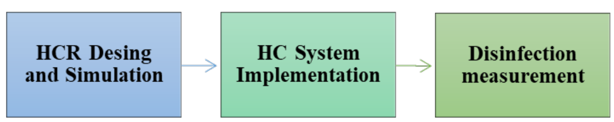

Figure 2. Methodologic Scheme. Source: created by the authors.

2.1 HRC Design and simulation

The reactor for hydrodynamic cavitation was designed with a venturi-type geometry and started with computational fluid dynamics (CFD) simulation of the fluid dynamics using finite elements. The simulations were developed in Solid Work®.

For the simulation, it is fundamental to understand the physics associated with the phenomenon of cavitation, which can be defined as the formation of vapor or gas bubbles in a liquid due to the pressure variations to which it is subjected. The intensity of cavitation causes extreme phenomena to occur in the flow of a fluid [39], including mechanical effects, such as the generation of turbulence and the increase in the liquid-vapor phase transition on the boundary surface of the bubbles, generated due to the reduction of the pressure to below the vapor pressure; chemical effects, include the generation of hydroxyl radicals, ozone, and other chemical reactions; and thermal effects, as the increase temperature and pressure.

The intensity of cavitation is measured using a dimensionless parameter called the cavitation number, σ, which is mathematically deduced in a fluid flow from the Bernoulli equation, (1):

$$\frac{P_1}{\rho_1 g} + \frac{v_1^2}{2g} + H_1 = \frac{P_2}{\rho_2 g} + \frac{v_2^2}{2g} + H_2 \tag{1}$$

Where P_1 is the pressure at the inlet, ρ_1 is the fluid density at the inlet, v_1 is the fluid velocity at the inlet, P_2 is the pressure at the outlet, ρ_2, is the fluid density at the outlet, v_2 is the fluid velocity at the outlet, H_1 is the fluid height at the inlet, H_2 is the fluid height at the outlet, y g is the acceleration due to gravity. If it is assumed that the fluid is at the same height, terms H_1 and H_2 cancel out, so (1) is transformed into (2):

$$\frac{P_1}{\rho_1} + \frac{v_1^2}{2} = \frac{P_2}{\rho_2} + \frac{v_2^2}{2} \tag{2}$$

Rearranging (2) gives (3):

$$v_1^2 - v_2^2 = 2\left(\frac{P_2 - P_1}{\rho}\right) \tag{3}$$

When divided by input velocity v_1^2, the relationship is transformed into (4):

$$1 - \frac{v_2^2}{v_1^2} = \frac{P_2 - P_1}{\frac{\rho\, v_1^2}{2}} \tag{4}$$

The left-hand side term in (4) is known as the dispersion factor or cavitation number, σ_v. Suppose the pressure at the inlet of the restriction is low enough for the water to reach its vapor pressure, and the inlet velocity is that of the restriction (typically an orifice). In that case $P_1 = P_v$ y $v_1 = v_h$, and the cavitation number can be expressed according to (5):

$$\sigma_v = 1 - \frac{v_2^2}{v_h^2} = \frac{P_2 - P_v}{\frac{\rho\, v_h^2}{2}} \tag{5}$$

This number can be interpreted in two ways: first, it is the ratio between the energy of the fluid due to its pressure, which is associated with the term $\left(\frac{P_2 - P_v}{\rho}\right)$, and the maximum kinetic energy, which is associated with the term $\left(\frac{v_h^2}{2}\right)$. Second, σ_v can be understood as the ratio between the total pressure drop and the dynamic pressure that occurs due to the inlet velocity. A change in absolute pressure is related to a change in the flow rate, so the dynamic pressure can be considered to define the size of the pressure drop, which results in the formation and growth of cavities. Alternatively, the cavitation number can be defined according to (6):

$$\sigma_p = \frac{Recoverid\ Pressure\ Differential}{Total\ Pressure\ Differential} = \frac{P_2 - P_v}{P_1 - P_2} \tag{6}$$

A low cavitation number means high cavitation intensity since the dynamic pressure forms the cavities. To ensure a low cavitation number, the denominator of (5) and (6) must be increased, and the numerator must be decreased, which is achieved by increasing the inlet pressure, P_1, increasing the velocity at the restriction, v_h, decreasing the outlet pressure, P_2, or increasing the vapor pressure, P_v, which can be achieved by increasing the temperature.

The adjustment of the cavitation process parameters generates two significant engineering problems:

a. If $P_2 - P_v$ is small, then the discharge pressure resembles the vapor pressure of the water so that it could erode the elements downstream of the fluid stream (elbows, valves, and others).
b. If $\rho\, {v_h}^2$ is large enough, supersonic flow could be achieved, which would cause considerable energy expenditure.

Bernoulli's conservation theorem shows that for a high velocity, it is necessary to increase the pump's capacity, which impels the fluid in pressure or flow rate. If $P_1 - P_2$ is required to be very large, more powerful pumps are needed to overcome this hydraulic loss, which would increase energy costs.

Therefore, a rigorous process of evaluating cavitation and disinfection parameters is necessary before carrying out experimental tests to avoid high investments and damage to equipment. For this, using CFD is fundamental as an analysis tool that enables the creation of complex models that make it possible to manipulate variables and parameters for decision-making. Through CFD, the behavior of a fluid in any system is calculated with precision so that its velocity fields, pressure, transported variables, reactions produced inside the fluid, the interaction between different phases, and, in short, any characteristic derived from the state and nature of the fluid can be known [40].

The CFD simulation with finite elements followed the general steps suggested in [41]. A Venturi shape was used for the disinfection element's geometry, as shown in Figure 3, after a comparative evaluation with other geometries, such as the orifice plate and fins.

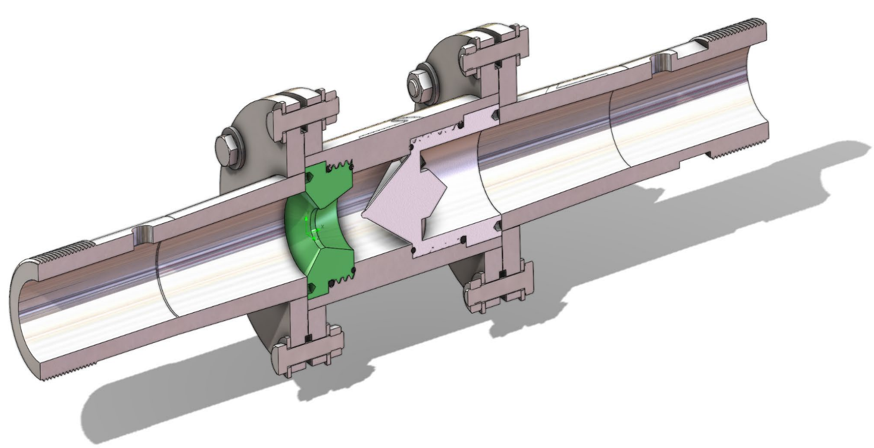

Figure 3. Geometry of a disinfection element by cavitation. Source: created by the authors.

Figure 4 shows the mesh refinement at specific geometry points, with five being the highest and 0 being the lowest. Discretization or meshing process, with refinements according to the overlapping areas of the geometry and considering the possibility of high gradients in the study values, yielded the following results:

a. Total cells and fluid cells: 119103.
b. Fluid cells in contact with solids: 67760.

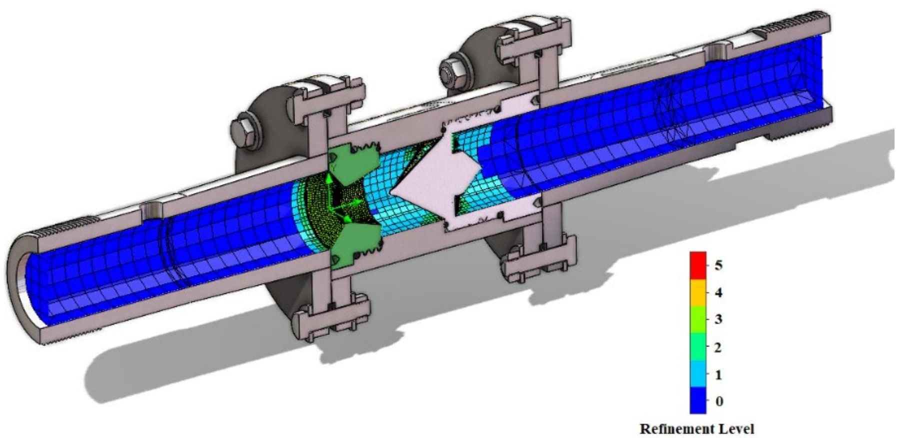

Figure 4. Discretization of the CFD model of the cavitation disinfection element.
Source: created by the authors.

To develop the fluid simulation, SolidWorks® numerically solves the Navier-Stokes equations, which are expressions of the conservation laws of mass, momentum, and energy (7), (8), and (9), [42], [43], where ρ is the fluid density, V its velocity, $\tau_{ij}$the viscous stress tensor, p its pressure, F the forces acting on the flow, e is the internal energy, Q is the heat source, t is the time, Φ is the dissipation and $\nabla . q$ is the heat lost by conduction. The simulation time was approximately 15 hours, which was necessary to observe the convergence of the desired parameters (pressure, velocity, density, vapor volume fraction) in 2810 iterations.

$$\frac{\partial \rho}{\partial t} + \nabla .(\rho V) = 0 \tag{7}$$

$$\rho \frac{\partial V}{\partial t} = \nabla . \boldsymbol{\tau}_{ij} - \nabla p + \rho F \tag{8}$$

$$\rho \frac{\partial e}{\partial t} + p(\nabla . V) = \frac{\partial Q}{\partial t} - \nabla . \boldsymbol{q} + \boldsymbol{\Phi} \tag{9}$$

The calculation of σ_v used (5), considering P_2 as the average pressure at the outlet of the computational domain of the simulation, P_v as the minimum pressure obtained in the simulation (which does not necessarily coincide with the vapor pressure of water at room temperature but must be equal to or less than), and v_h as the maximum velocity obtained in the simulation, which corresponds to the restriction and orifice designed.

2.2 HC system implementation

Figures 5 and 6 detail the system assembly diagram. The main components used in the laboratory tests were: (1) the Venturi cavitation element, (2) a 6 HP centrifugal pump, (3) a

300 L domestic wastewater storage tank, (4) a flow diversion, (5) pressure gauges, (6) a sampling circuit, (7) the system water outlet, (8) the recirculation circuit and (9) a by-pass circuit. The system operated with a 6 HP pump power, a 2" suction and 1.5" discharge, and a flow rate of 0.00625 m^3/s (6.25 L/s). With the implemented system, the designed cavitation equipment performance tests were carried out.

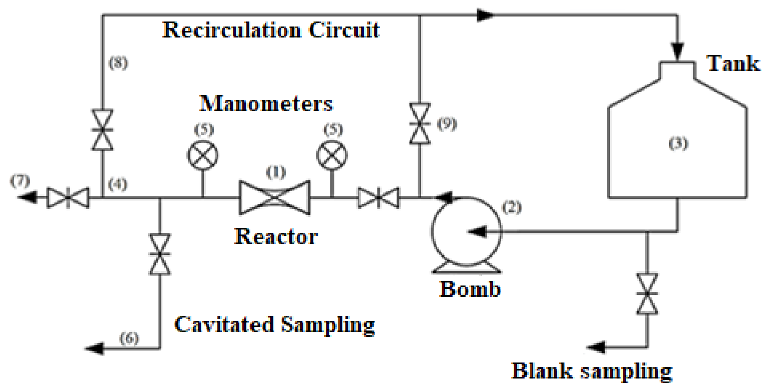

Figure 5. Schematic diagram of the test circuit for the Venturi cavitation system. Source: created by the authors. The numbers marked in Figure 5 correspond one by one with the elements in Figure 6.

2.3 Disinfection percentage measurement

During the experimental stage, point sampling of wastewater was carried out in a discharge on the Fonce river in the municipality of San Gil, Santander, Colombia, on a property owned by the Santander Energy Company in the El Porvenir neighborhood. Wastewater samples were taken both upstream and downstream of the cavitation system. Table 1 shows the characterization of the discharge.

In order to determine the performance of the system and its disinfection efficiency, laboratory analyses of the microbiological quality were carried out to count the CFU (Colony Forming Units) of total coliforms (Gram-negative bacteria, non-spore-forming) and fecal coliforms (specifically Escherichia coli, *E. coli*), according to the membrane filtration method, for all samples collected. The tests performed were filtered on a membrane and cultured in Chromoculth for 24 hours at 36.5 °C, with filtrate volumes for serial tubes of 10^{-4} and 10^{-5} of 9 ml with dilutions of 10^{-4} and 10^{-5}, following the standards of the Institute of Hydrology, Meteorology and Environmental Studies (Sub directorate of Hydrology - Environmental Quality Laboratory Group, Total Coliforms and *E. Coli* by membrane filtration on Chromocult agar, August 2007), Resolution 2115 of 2007 of the Ministry of Social Protection, Ministry of Environment, Housing and Territorial Development, and SM 9222 J (Simultaneous Detection of Total Coliform and *E. Coli* by Dual-Chromogen Membrane Filter Procedure).

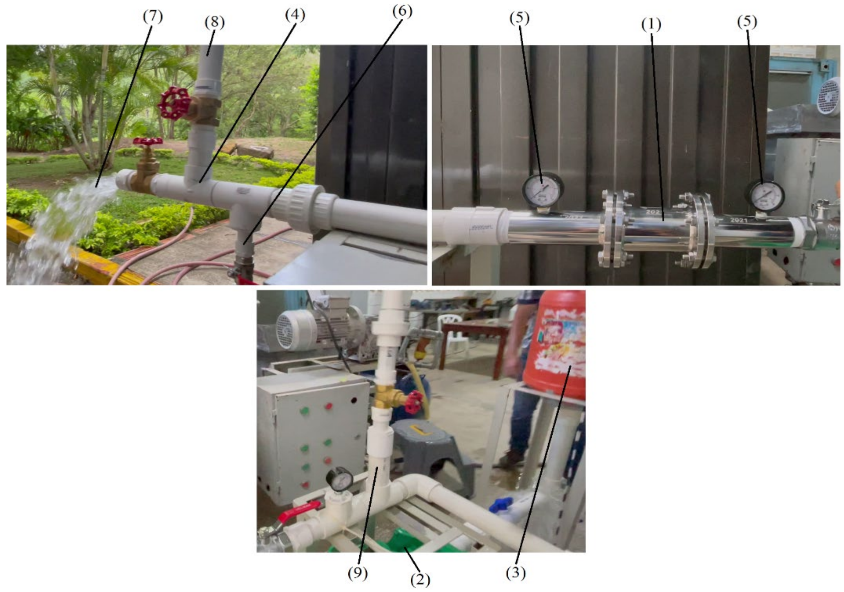

Figure 6. Physical assembly of the test system for the Venturi cavitation team. Source: created by the authors. The numbers marked in Figure 6 correspond one by one with the elements in Figure 5.

Table 1. Characterization of the Discharge. Source: created by the authors.

	DQO mgO_2/L	DBO5 mgO_2/L	SST mg/L	SS mg/L	SSD mg/L	Conductivity S/m
Dumping selected	850	373	905	338	5,2	1169
	Turbidity NTU	pH	T°C	Col.T UFC/100ml	E. coli UFC/100ml	Meso. UFC/100ml
	377	7.68	28.4	1.890.000	4.880.000	6.780.000

The growth of bacteria was evaluated in triplicate for three different amounts of water recirculation (n_p) in the cavitation system (1, 10, and 20). In each experiment, the system loading volume was 1000 mL of domestic urban wastewater (DUW) per 15 L of non-residual water in the tank. The total water volume processing was 200 L (12.5 L of DUW, diluted in 187.5 non-residual water). The number of recirculation was calculated measurement the time, knowing that for a flux of 6.25 L/s, with a tank of 200 L, one pass occurs each 32 s. Figure 7 shows an example of the bacterial growth obtained in the laboratory for the three amounts of water recirculation.

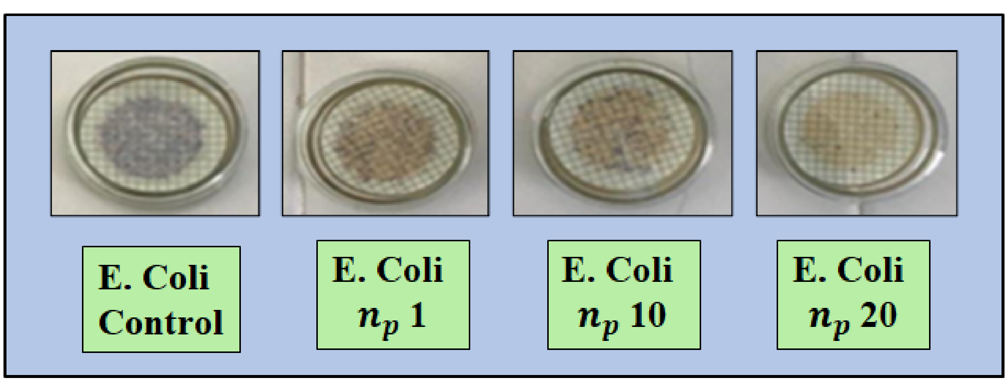

Figure 7. E. Coli samples on Agar. Source: created by the authors.

The methodology followed in the present investigation to evaluate the inactivation of contaminating microorganisms corresponds to the methods commonly used for this type of work [27]. Its scope goes up to evaluating index or indicator microorganisms, whose identification at certain levels reveals the potential presence of pathogenic microorganisms with taxonomic or physiological relationships. To evaluate each microorganism considered pathogenic in a specific medium in a separate form is beyond the limits set for the present study. As mentioned, most of the literature does not specify each pathogenic organism. However, studies have been done to characterize broad groups, such as the coliform group, which are fundamental indicators of contamination according to environmental standards. Generally, the literature reports results for *E. coli*. This study broadens that spectrum and presents results for the critical indicators of total and fecal coliforms. The research on fecal coliforms has been explicitly based on *E. coli*, the leading indicator of fecal contamination. Identification of parasites, protozoa, or viruses is beyond the scope of this study.

To minimize the matrix effect, i.e., the influence of the composition of a sample on the detection and quantification of microorganisms, in each test carried out, an analysis of blank samples has been performed, the sterility of the culture media and materials has been examined, and tests have been developed with a known concentration of microorganisms, following the standard rules for this type of tests, in order to minimize possible interferences that the analytical methods may cause.

3. RESULTS AND DISCUSSION

3.1 Simulation results

Figure 8 shows the high and low levels of the hydrodynamic variable (in red and blue, respectively). These flow parameters give a better idea that the cavitation process is happening, and that the specific spatial location designed for the purpose of cavitation is taking place there and not in another place that could damage other components not designed for those conditions.

The simulation verified that the levels of the hydrodynamic variables obtained were consistent. Thus, for example, when detecting a cavitation zone at a pressure of 2300 Pa (vapor pressure at 20 °C), a value significantly below 1000 kg/m^3 was found in the density parameter. These hydrodynamic parameters are beneficial for determining conditions that are associated with effective disinfection, including:

a. High velocity, near 35 m/s (Figure 8a).
b. Low pressure, below vapor pressure (<2300 Pa, Figure 8b).
c. Vorticity, or the ability of the flow to form vortices which is desirable if you want to increase the probability that an imploding cavitation bubble will encounter an E. Coli bacterium [44] (Figure 8e).
d. The density of water under environmental conditions at 1 atmosphere and 20 °C is 998 kg/m3 (Figure 8c). Because water is considered incompressible, a low density implies that there are zones within the computational domain of the simulation that have already transitioned to a vapor-liquid mixture state (Figure 8d). In the case of the simulation, as can be seen in Table 2, there were zones where the water reached 5.74 kg/m3, which indicates that the process is already generating cavitation bubbles.

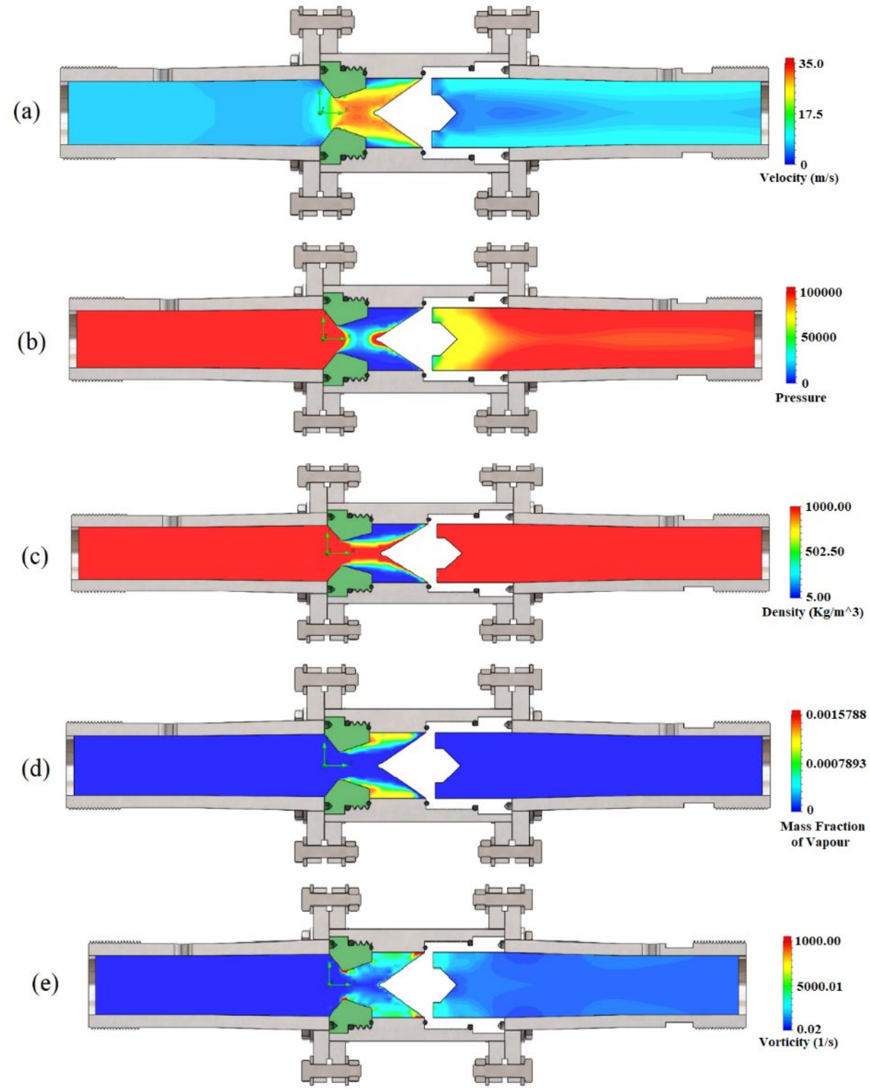

Figure 8. Evaluation results in the HCR CFD simulator. (a) Velocity (b) Absolute pressure (c) Water density (d) Mass fraction of water vapor and (e) Vorticity. Source: created by the authors.

Once the hydrodynamic parameters of cavitation were determined, the cavitation number was calculated, as detailed in Table 2, obtaining a result of σ_v =0.07. This value of the cavitation number (0.07) is close to the lower limit reported by [45], who refer, for microorganism reduction, an optimal interval for σ_v between 0.1 and 0.54. Likewise, [33] shows how σ_v lower than 0.2 is related to a more significant logarithmic reduction of microorganisms. Whether this σ_v value causes a critical cavitation in the experimental reactor that affects its structure has not been determined. The most probable cavitation zone is shown in Figure 9.

Table 2. CFD simulation results. Source: created by the authors.

Input		Geometry	Venturi	Desirable trend
		V_1 (m/s)	6.644	Design criteria
		Setting	n=1 d=18.52 mm	Design criteria
Output	General Param.	V_h (m/s)	43.430	Higher value
		Minimum density	5.74	Lower value
		P_2 (Pa)	125569.39	Lower value
		Cross-sectional area. Pump discharge flow (m^2)	0.001	Design criteria
		Cross-sectional area. Cavitator constraint (m^2)	2.694E-04	Lower value
		β (-)	0.24	Lower value
		Cavitator flow (L/s)	5.33	Lower value
		Power (HP)	1.863	Lower value
	Evidence of cavitation	Cavitation number σ_v (-)	0.07	Lower value
		Cavitation number σ_p (-)	0.1720	Lower value
		Average density (kg/m^3)	997.55	Lower value
		Minimum density (kg/m^3)	5.74	Lower value
		P_v Minimum pressure (Pa)	1037.26	Lower value
		Frac. Volum. average steam (-)	5.226E-04	Higher value
		Frac. Volum. maximum steam (-)	0.99994	Higher value
		Frac. Average steam mass (-)	1.868E-07	Higher value
		Frac. Maximum steam mass (-)	1.00000	Higher value
	Desirable effects	Vorticity (1/s, max)	117629.00	Higher value
		Turbulence intensity (%, max)	1000	Higher value
		Dissipation in turbulence (W/kg)	3.98E+05	Higher value
		Turbulence energy (J/kg)	126.676	Higher value

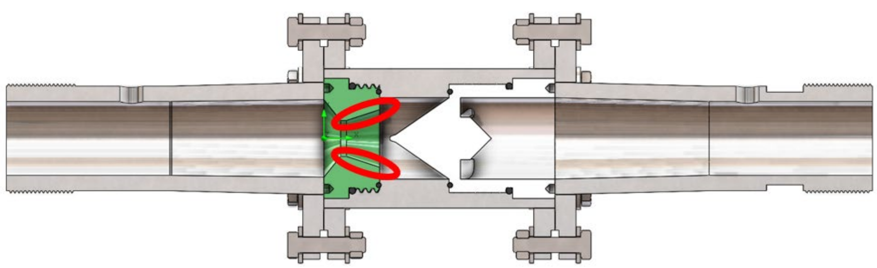

Figure 9. Most probable cavitation zone. Source: created by the authors.

3.2 Disinfection results

How hydrodynamic cavitation affects microorganisms obeys a sequence of abrupt generation and collapse of bubbles [31] because of pressure variations in the liquid, which are generated in turn by the speed variations caused by the reactor. As the velocity increases, the pressure decreases and bubbles emerge. Then, as the velocity decreases, the pressure increases, and the bubbles collapse. This abrupt generation and collapse of bubbles inside the reactor produces increases in temperature and pressure, which can reach values close to 10000 K and 1000 atm, in time instants of the order of microseconds. These values are sufficient to generate ruptures in the cell membrane of the microorganisms present in the water and generate free radicals that can contribute to altering the DNA of the microorganisms present.

For the σ_v value obtained in simulation (0.07), and with a registered pressure delta of 54 psi, the microbiological test data determined for $n_p = 1$, $n_p = 10$, and $n_p = 20$, correspond to those detailed in Tables 3 and 4, where C and C_0 are the number of coliforms measured in UFC/100 mL (colony forming units per 100 mL) after and before cavitation, respectively. C/C_0 is the ratio between the number of coliforms after and before cavitation, GIR is the growth inhibition rate calculated according to (10), and LR is the logarithmic reduction calculated according to (11).

$$\boldsymbol{GIR} = \frac{100(|C - C_0|)}{C_0} \tag{10}$$

$$\boldsymbol{LR} = Log_{10}\left(\frac{C_0}{C}\right) \tag{11}$$

Table 3. *E-coli* bacterial death evaluation tests, with dilution to 10^{-4}. Source: created by the authors.

Coliforms in serial tubes 10^{-4}		Experiment 1			Experiment 2			Experiment 3		
		n_p			n_p			n_p		
		1	10	20	1	10	20	1	10	20
Total Col.	C	278	298	24	230	196	64	257	115	41
	C_0	359	359	359	314	314	314	327	327	327
	C/C_0	0.774	0.830	0.067	0.732	0.624	0.204	0.786	0.352	0.125
	GIR	22.56	16.99	93.31	26.75	37.58	79.62	21.41	64.83	87.46
	LR	0.11	0.08	1.17	0.14	0.20	0.69	0.10	0.45	0.90
E. coli	C	91	63	31	91	59	22	156	72	31
	C_0	123	123	123	122	122	122	218	218	218
	C/C_0	0.740	0.512	0.252	0.746	0.484	0.180	0.716	0.330	0.142
	GIR	26.02	48.78	74.80	25.41	51.64	81.97	28.44	66.97	85.78
	LR	0.13	0.29	0.60	0.13	0.32	0.74	0.15	0.48	0.85

Table 4. E-coli bacterial death evaluation tests, with dilution to 10^{-5}. Source: created by the authors.

Coliforms in serial tubes 10^{-5}		Experiment 1			Experiment 2			Experiment 3		
		n_p			n_p			n_p		
		1	10	20	1	10	20	1	10	20
Total Col.	C	109	46	13	107	48	21	159	106	58
	C_0	197	197	197	164	164	164	189	189	189
	C/C_0	0.553	0.234	0.066	0.652	0.293	0.128	0.841	0.561	0.307
	GIR	44.67	76.65	93.40	34.76	70.73	87.20	15.87	43.92	69.31
	LR	0.26	0.63	1.18	0.19	0.53	0.89	0.08	0.25	0.51
E. coli.	C	42	11	4	45	17	14	74	37	21
	C_0	82	82	82	95	95	95	111	111	111
	C/C_0	0.512	0.134	0.049	0.474	0.179	0.147	0.667	0.333	0.189
	GIR	48.78	86.59	95.12	52.63	82.11	85.26	33.33	66.67	81.08
	LR	0.29	0.87	1.31	0.32	0.75	0.83	0.18	0.48	0.72

The best results were obtained by Experiment 1 with dilution of 10^{-5}, reaching a GIR of 93.40 % and a LR of 1.18 for Total Coliforms, and a GIR of 95.12 and a LR of 1.31 for E. coli. Averages of disinfection ratios (C/C_0) and average of GIRs for one, ten, and twenty water recirculation for both total and fecal coliforms and dilutions 10-4 and 10-5 can be seen in Figures 10 and 11, respectively. The average growth inhibition rates for one, ten, and twenty recirculation were 31.72 %, 59.45 %, and 84.53 %, respectively, reached in approximate times of 32, 320, and 640 seconds, considering the system's flow rate. In [46] with an HCR with an orifice plate, after 1800 seconds, the removal rate was 41.57 % for an initial *E-coli* density of 0.16×10^6/100 mL, reaching, however, a removal greater than 98 % after 60 minutes. On the other hand, when comparing the results with [27], it is evident that the C/C_0 levels for *E-coli* reported in this work for disinfection reactors with an orifice plate are approximately 50 % higher than those determined in the present research for comparable initial C_0 conditions.

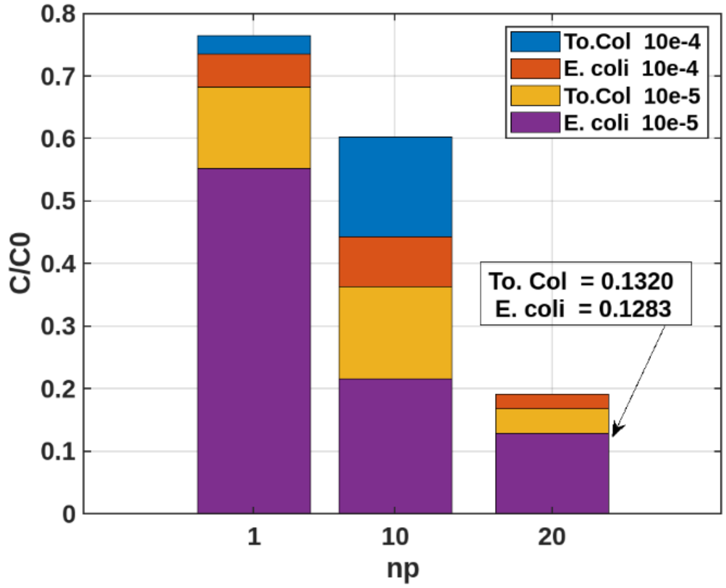

Figure 10. C/C_0 averages for the three experiments. Source: created by the authors.

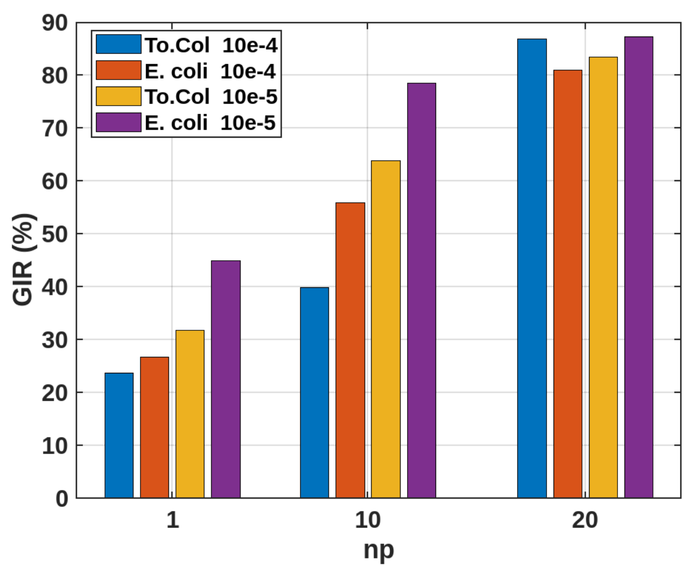

Figure 11. GIR (%) averages for the three experiments. Source: created by the authors.

The following table (see Table 5) compares the results of this research and those of other related works for the specific indicator of *E. coli*. The GIR results of this research are close to those obtained by other laboratory studies that were realized with artificially contaminated distilled water samples and for a smaller volume of water. It could be helpful for future experiments to mix HC with advanced oxidation methods to increase the LR value.

On the other side, after cavitation, the mean pH measurements in the tank's water were 7.80. Before cavitation, the pH of the 187.5L mixed with the 12.5L of DUW was 7.73, and 7.68 in the direct sample of DUW. This increase in pH after cavitation could be understood by the formation of free radicals of OH-1 during the HC.

Table 5. E. coli results comparison. Source: created by the authors.

Author	Environment	Microorganisms reduced	C_0 Order (UCF/mL)	Maximum GIR / LR	Reactor	Vol. (L)	Recirculation time (min)
Present Study	Laboratory samples of natural: discharge over a river	*E. coli*	10^7	GIR:95.12 LR:1.31	Venturi-type geometry	200	0.6
[31]	Laboratory. Distilled water	*E. coli*	10^3	GIR: 99 % LR: Nr*	Vortex Diode	12	60
[32]	Laboratory. Distilled water	*E. coli*	10^4	GIR:100 % LR: Nr*	Vortex Diode and Natural oils	20	90
[33]	Laboratory. Distilled water	*E. coli*	10^6	GIR:100 % LR: 6.57	Rotary	15	4

Nr* No reported.

From the results obtained, it was also possible to determine the CFU/J, or colony-forming units dead per Joule of energy. Considering that the pump operates in three-phase mode with a line voltage of 220 V, a line current of 11 A, and a power factor of 0.86, its electrical power was calculated at 3730.4 W. With this power, and given that the system's flow rate (6.25 L/s) empties the 200 L tank in 32 seconds, the Joules consumed (J_C) for one pass were calculated at 119.375,7. Now, knowing that the discharge water has 4.88x10^6 CFU/100 mL (CFU_{100mL}), that the liters of domestic urban wastewater (L_{udw}) used in each experiment were 20, and that the average GIR for one pass (GIR_{avg}) can be estimated from Tables 3 and 4 at 31.2 %, the CFU/J can be calculated according to (12), at 2327.6. This result is higher than that reported by [47], which reports an approximate value of 1038 CFU/J, with only cavitation.

$$\frac{\boldsymbol{CFU}}{\boldsymbol{J}} = \frac{10 * CFU_{100mL} * L_{udw} * GIR_{avg}}{J_c} \tag{12}$$

4. CONCLUSIONS

A physical system for treating domestic urban wastewater through hydrodynamic cavitation in a Venturi-type reactor was designed with the aid of CFD simulation. This simulation was crucial in determining the zone of most likely cavitation and the cavitation number, estimated at 0.07. With a flow rate of 0.00625 m^3/s, a pressure delta of 54 psi, and a water volume of 200 L, the system was evaluated with samples of wastewater discharged into the Fonce river in San Gil, Santander, Colombia (12.5 L of DUW, diluted in 187.5 non-residual water), with 4.88x106 CFU/100 mL. In total, nine tests were carried out, which showed average growth inhibition rates of 31.72 %, 59.45 %, and 84.53 % for one, ten, and twenty water recirculation, with an energy efficiency of 2.327.6 CFU/J. The higher results were obtained in a dilution of 10^{-5}, reaching a GIR of 93.40 %, an LR of 1.18 for Total Coliforms, and a GIR of 95.12 % and an LR of 1.31 for *E. coli*. Cavitation increases the pH of the water processing from 7.73 to 7.80, which could be a consequence of free radicals OH^{-1} formation. The comparison of results obtained with those reported by important bibliographic references shows that the technology is promising, efficient, and operationally attractive for implementation in direct discharge points. However, a greater number of tests are necessary to consolidate its development.

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CONFLICT OF INTERESTS

The authors declare that they have no conflict of interest.

AUTHORSHIP CONTRIBUTION

Freddy Alexander Jara-Mora: Realized the CFD and the mechanical design of the system.
Frank Carlos Vargas-Tangua: Conceived and designed the microbiological analysis.
Jorge Alberto Neira-Tavera and Luis Eduardo Cobos-Ramírez: Conceived and designed the instrumentation system and its automatization.
Wilson Gamboa-Contreras: Contributed with analysis tools.
Milton J. Muñoz-Neira: Performed the analysis tools and wrote the paper.

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