Journal of Agricultural Science; Vol. 15, No. 2; 2023
ISSN 1916-9752 E-ISSN 1916-9760
Published by Canadian Center of Science and Education

Design of Venturi-Type Fertilizer Injectors to Low-Pressure Irrigation Systems

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Received: November 8, 2022 Accepted: December 6, 2022 Online Published: January 15, 2023

doi:10.5539/jas.v15n2p25 URL: https://doi.org/10.5539/jas.v15n2p25

Abstract

Twenty prototypes of Venturi-type fertilizer injectors for low-pressure agricultural irrigation systems were designed based on functional hydraulic pressure head and variation of their structural designs. These prototypes were modelled in three dimensions (3D) and evaluated using simulation through Computational Fluid Dynamics software (CFD). The main structural design characteristics come from a real necessity to complement an low pressure multigate irrigation system project named in Spanish "El Manzano" (The Apple tree) and bring it the fertigation possibility. The aim of this research was to select the best prototype, in order to identify the convergent and divergent angles, throat diameter and hydraulic pressure head to efficiently produce a Venturi-type injector for use in gated-irrigation pipe irrigation systems for use in a future in "El Manzano" project. As a result of the simulations, the physical characteristics of the injector were defined. The inlet and outlet diameters should be 152.4 mm, the throat diameter 76.2 mm and the suction diameter of 50.8 mm. The convergent and divergent angles showing most improved performances were 7.5 and 10°, respectively. This methodology can be used to construct Venturi-type fertilizer injectors for low-pressure gated-pipe agricultural irrigation systems, which, on one side, can reduce significantly the fertilizer application costs and, on the other side, the fertilizer management efficiency can be also improve considerably to save water resources. There is relatively very little experience in using this type of fertilizer injectors in low-pressure irrigation systems.

Keywords: agricultural fertigation systems, Computational Fluid Dynamics (CFD), computational simulation, fertigation, low-pressure irrigation, Venturi injectors

1. Introduction

Injection of fertilizer into the water-flow used for irrigation (fertigation) is a useful process for dissolving and applying plant nutrients (Domínguez, 1996; Martínez, 2005). The Venturi-type injector is a common mechanism for applying fertilizer (Kumara, Singha, & Singlaa, 2012). Mataix (2005) defined the Venturi-type injector as "a device with a convergent section, followed by a throat and a divergent section gradually returning to the initial diameter".

A Venturi-type injector generates suction due to a negative pressure differential that occurs between its inlet and outlet by reducing its throat diameter in the middle, which accelerates the fluid by reducing the pressure. This suction is used to pull a solution of water and fertilizer into the Venturi-type mechanism for injection into the irrigation system. Inlet pressure is translated into kinetic energy as the fluid passes through the injector throat. Increased inlet pressure and discharge velocity increase the kinetic energy in the throat. When it reaches a certain level, the energy from the pressure in the throat is reduced, creating a negative pressure for stabilization. The rate of fluid entrance (dissolved fertilizer and water) at the inlet to the Venturi mechanism increases significantly with decreasing inlet pressure (Kumar, Rajput, & Patel, 2012; Manzano, Palau, Benito, Guilherme, & Vasconcelos, 2016). The kinetic energy and the pressure drop in the throat also increase very rapidly with increasing fluid velocity (Fan & Kong, 2013). Moreover, the injection rate in the injector has a significant effect on the uniformity of fertilizer distribution (Regina, Richard, & Roger, 2003) and in the stability of the fertirrigation system while it is in operation, and in this sense the Venturi-type injectors show greater uniformity compared with differential pressure tank method which uses proportioner pump performed (J. Li, Meng, & B. Li, 2007) or at least both Venturi injectors and pump performance shows a similar performance (da Costa Santos & Zocoler, 2018).

Some authors have noted that the design for a Venturi-type injector is defined by convergent angles (θc) of 10.5 and 21° (Reader-Harris, Brunton, Gibson, Hodges, & Nicholson, 2001), and divergent angles (θd) of 5 and 7°. Companies such as Mazzei Vicamp are marketing fertilizer injectors with this design (VICAMP, 2002), but at small sizes. Yet, Zárate (1995b) indicated that high yields in terms of energy use (lower head losses), can be made with the suction of a second fluid having a θc = 7.5° in comparison to θc at 5 and 7°.

Lima-Neto and de Melo Porto (2004) mentioned that commercial Venturi-type injectors do not exceed the efficiency obtained by a pressurized system with conventional injection pumps. However, their construction for solving specific problems exceeds, by two or three times, the efficiency of a commercial Venturi tube. Thus, a better cost-benefit ratio is obtained, approaching the efficiency developed for a pump. Lima-Neto (2006) evaluated Venturi-type injectors and determined that more efficient use is achieved when the suctioned fluid is denser.

Venturi-type injectors are technically feasible and their construction cost is relatively low as used by Vargas, René, and Huaita (2008b). These authors reported relationships that demonstrate the principles of the Venturi effect, and highlighted some key features that should be taken into account in their design, such as the convergent and divergent angles, and throat diameter. These authors tested different angles for the construction of these devices, but their research was conducted on drip irrigation systems where pipe diameters are relatively small and require a system of pressurized pipes.

Given a minimum differential pressure existing in the device, sufficient suction for use is generated, and these values can be computed prior to their construction given the availability of computational fluid dynamics software (CFD) for simulation, where the simulation and actual results will be similar (Baylar, Aydin, Unsal, & Ozkan, 2009; Manzano Juarez et al., 2014). CFD is an easy method to evaluate quickly a hydraulic systems (Bayón, Vallés Morán, Macián Pérez, & López Jiménez, 2017).

Critical pressure differences (*i.e.*, the limit where injection is no longer efficient), and the maximum operating pressure correlate linearly with inlet pressure (Santos, Zocoler, Justi, Silva, & Correia, 2012). The flow rate into a Venturi injector increases with increasing inlet pressure, or the pressure difference between inlet and outlet. If this differential pressure is small, then, the diameter of the suction port for the fertilizer-water solution should be decreased to increase the relationship with the injection rate. As well, the throat diameter and the convergent and divergent angles should be increased to improve injector performance (Yan, Chu, Wang, & Ma, 2010).

The pressure loss caused by using Venturi injectors for fertilizer decreases the quality of fertilization and irrigation uniformity (Yan, Chen, Chu, Xu, & Wang, 2012), for which the structural parameters should be optimized for better performance and to avoid losses.

Thus, the throat diameter influences the internal flow through the injector throat, the divergent angle influences the performance and efficiency of injection in the Venturi mechanism, and the ratio of convergent to divergent angles have greater influence on performance injection than the throat diameter. Yan and Chu (2011) noted that the best ranges for the ratio of convergent to divergent angles are 1:2 and 1:3, for maximum efficiency.

Hydraulic parameters include convergent angles and throat diameter, and divergent angles can be determined using CFD software (Perumal & Krishnan, 2013; Sun & Niu, 2012). The relation with throat constriction is the main factor influencing performance of a Venturi injector (Sun & Niu, 2012). The relation is positively correlated with the outlet velocity, and negatively correlated with critical pressure, minimum tube pressure, the coefficient of local pressure loss, and fertilizer absorption.

One of the current advantages offered by computer systems is the use of CFD software to conduct simulations of real phenomena or processes (Íñiguez Covarrubias, Flores Velázquez, Ojeda Bustamante, Díaz Delgado, & Mercado Escalante, 2015). Shannon (1998) described a simulation as "*the process of designing a model of a real system and conducting experiments with this model for the purpose of understanding the behaviour of the system and /or evaluating various strategies for the operation of the system*". According to Guash, Piera, and Casanovas (2009), it is now possible to generate outputs for the creation of statistical models to evaluate processes with simulated results.

Therefore, to reduce the effect of the pressure difference between inlet and outlet required by Venturi-type injectors, and to improve injection efficiency, the best option for calculating and determining the ideal structural parameters is simulation using computer software (Yan, Chen, Chu, Xu, & Wang, 2013a). Analyses of the results from simulation processes allows for selection of injection rate into the flow device. Injection rate is achieved with a constant pressure at the inlet of the injector, so the installation of a pressure regulator valve upstream of the Venturi device is recommended to avoid interior turbulence. Han, Huang, Liu, Wu, and Fan (2013) showed that the amount of fertilizer suction and discharge was directly affected by the inlet and outlet pressures. They also concluded that a device designed according to the requirements of the system results in a better performance than any one trademarked product.

The aim of this research was to select the best prototype, in order to identify the convergent and divergent angles, throat diameter and hydraulic pressure head to efficiently produce a Venturi-type injector for use in Agroecosystems with a low pressure gated-irrigation pipe irrigation systems, specifically for use in a future in "El Manzano" project. For this type of irrigation system there are little Venturi-type injectors on the market to facilitate and improve application efficiency of fertilizers.

2. Method

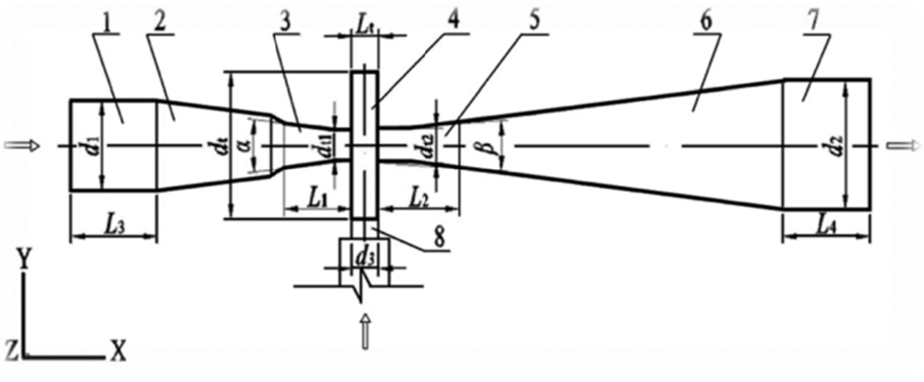
This research was conducted at Colegio de Postgraduados, Campus Veracruz, in Veracruz, Mexico, and consisted of six stages: Status of multi-gated irrigation systems in the study area; Design and modelling of 20 prototypes; Conducting simulations with the designed prototypes; Analysis of the resulting simulation data; Statistical conclusions; Construction of the prototype with the best performance.

Stage 1: Status of low-pressure gated irrigation systems in the studied area. Field visits were carried out to assess the operational status of the low-pressure gated irrigation system used to irrigate sugarcane. Data on irrigation systems were: pipe diameters (152.4 mm), hydraulic mean gradient (1.11%), Hydraulic head (0.7 kg/cm^2) and hydraulic flowrate (35 l/s), which were acquired from a previously published study of "El Manzano" project. This project was focused on the design of an irrigation system using low-pressure gated pipe line in The Irrigation District 035, La Antigua, Veracruz, Mexico (Landeros, 2003). It also was oriented to make a more efficient use of irrigation water among sugarcane plots by means of tubing the water to avoid evaporation, infiltrations and runoff losses through a network of low pressure pipes. There are telescopies pipes till 60.96 cm until 17.78 cm (the inner pipe diameter being six inches). Finally, the water is being distributed, at plot level, by 15.24 cm pipes with multi gates pipeline. "El Manzano" project uses an irrigation depth of 12 cm; an application efficiency of irrigation that varies from 75 to 80 % approximately. It was recommended to sugarcane producers to stablish furrows with a length of 120 m in order to prevent irrigation losses water. All these data were taken to design the Venturi type injectors prototypes. The basic data to design "El Manzano" project included soils, crops, climate, slopes and hydraulic characteristics of the studied area.

Stage 2: Design and modelling of 20 prototypes. The design of the prototypes of the Venturi-type fertilizer injectors is founded on the scientific method, and is based on fluid mechanics, such as the Continuity Equation, Bernoulli's Theorem, and the Venturi Tube Model Equation. An application of these principles was presented by Vargas, René, and Huaita (2008a) and designed according to Feitosa Filho, Pinto, and de Arruda (2018).

Twenty prototype models of Venturi-type fertilizer injectors were designed in 3D using the software *SolidWorks*® 2014. The characteristics for the prototypes differed and were defined by modifying their convergent and divergent angles, their inlet and outlet diameters, and throat diameter according to according to the structure suggested by Sun and Niu (2012) (Figure 1). The throat diameter was determined considering the minimum flow rate required for the irrigation system in the study area (35 l/s). Given that the loss of energy due to friction depends on the flow rate, the viscosity of the liquid, and material from which the Venturi-type injector is constructed, the largest diameter possible to decrease the loss is considered. In the present study, the diameter selected for the injector inlet and outlet was 152.4 mm, the throat diameter was 76.2 mm, and the diameter of the fertilizer suction port was 50.8 mm.

To design the prototypes, it was used convergent angles of 7.5, 10.5 and 21°, as recommended for small injectors used for drip irrigation (Vargas et al., 2008a; Zárate, 1995a), and we added a fourth convergent angle of 16° (the latter angle was selected for testing because there were no references of tests between 10.5 and 21°). Five different divergent angles also were tested ranging from 6 to 10°. The design features used in the software *SolidWorks*® 2014 to produce the twenty 3D prototypes of Venturi-type fertilizer injectors are presented in Table 1.



1. Inlet connection; 2. Constriction zone II; 3. Constriction zone I; 4. Throat; 5. Diffuser part I; 6. Diffuser part II; 7. Outlet connection; 8. Injector inlet.

Figure 1. Internal structure for flow in a Venturi-type injector

Source: Sun and Niu (2012).

Table 1. Variables used by SolidWorks® 2014 to define the three-dimensional models for simulation. For all models: inlet and outlet diameter (D) = 152.4 mm throat diameter (d) = 76.2 mm and inlet fertilizer port diameter of 50.8 mm

Principal Angle	**Model**	**Convergent angle (θc)**	**Divergent angle (θd)**
21°	M1	21	6
	M2	21	7
	M3	21	8
	M4	21	9
	M5	21	10
10.5°	M6	10.5	6
	M7	10.5	7
	M8	10.5	8
	M9	10.5	9
	M10	10.5	10
7.5°	M11	7.5	6
	M12	7.5	7
	M13	7.5	8
	M14	7.5	9
	M15	7.5	10
16°	M16	16	6
	M17	16	7
	M18	16	8
	M19	16	9
	M20	16	10

To design the fertilizer injectors, it was essential to know the hydraulic fluid pressure charges and hydraulic spending. These served as parameters for determining other fluid properties for injector tests. Based on these two factors, was calculated the quantity of fertilizer absorption, fluid velocity, total pressure rate and injector efficiency.

For the design of the prototypes, the existing hydraulic pressure load in the multi-gate low-pressure irrigation system was taken as a basis. This was 0.7 kg/cm^2, and a system flow of 35 l/s taken from the “El Manzano Project”. The formulas for the calculations of said variables are mentioned below.

There are two common geometric variables in all Venturi-type injectors: the diameter of the pipe (D) and the diameter of the throttle or throat (d). The d/D ratio is known as the diameter ratio and is symbolized by the Greek letter β (beta) (IMTA, 2011). Table 2 shows the extreme values for D and β for a Venturi-type injector for low-pressure irrigation.

Table 2. Diameter value (D) and diameter ratio (β) for a Venturi type injector (IMTA, 2011)

Variable	**Value**
D_{min} (*mm*)	200
D_{max} (*mm*)	1200
β_{min}	0.40
β_{max}	0.70

To start the design, the flow rate of the device was determined using the following equation (IMTA, 2011):

$$Q = \frac{Cd}{\sqrt{1-\beta^4}}\frac{\pi}{4}d^2\sqrt{2gh_0} \quad (1)$$

where,

Q: Flow (m^3/s); *Cd*: Discharge coefficient (dimensionless); β: ratio of diameters d/D (dimensionless); d: injector throat diameter (m) and D inlet diameter (m); π: 3.1416; d: throat diameter (m); g: Acceleration of gravity (9.81 m/s^2) and h_o: Differential pressure (kg/cm^2).

The equation is applicable to non-compressible flows such as water and with the following conditions:

(1) The flow must be homogeneous; (2) The value of the differential pressure must be known precisely. (3) The conduit must work under pressure (full tube).

The rest of the formulas are mentioned below:

$$q = A\sqrt{2gh_0} \quad (2)$$

where,

q = Fertilizer absorption (m^3/s); A = Area (m); g: Acceleration of gravity (9.81 m/s^2); h_0 = Differential pressure (kg/cm^2).

$$N = \frac{e_2 - e_3}{e_1 - e_2} \quad (3)$$

where,

N = Total pressure rate; e = Injector ports.

$$M = \frac{q}{Q} \quad (4)$$

where,

M= Injection capacity (lps); q = Fertilizer absorption (m^3/s); Q: Flow (m^3/s).

$$\eta = M \cdot N \times 100 \quad (5)$$

where,

η = Efficiency (%); M = Injection capacity (lps); N = Total pressure rate.

The results of the calculated variables that were used for the development of the 20 prototypes in the simulations are shown in Table 5.

Stage 3: Conducting simulations with the designed prototypes. Using *SolidWorks FlowSimulator*® 2014, CFD software simulations were performed and the functional operation of the 20 designed prototypes was evaluated. Initially, the firsts simulations were carried out using pure water at 20 °C, and flow velocity was measured at the injector outlet, to select the best designs to be tested, subsequently, whit fertilizer characteristics into simulation. Flow velocity has a direct correlation with the hydraulic spending and pressure of the injector. A normality test on the data was performed, followed by an analysis of variance. All the simulations run for the described prototype considered the following boundary conditions: an environment pressure of 100 000 Pa; inlet injector flow rate equal to 0.035 m^3/s; income water-fertilizer mixture flow rate of 0.0187 m^3/min and an outcome injector flow rate of 0.029 m^3/s. There was a small margin of error or uncertainty because an ideal atmospheric pressure was assumed. However, when using said value in all the simulations, the induced error is discriminated. Similarly, the mesh for all the simulated prototypes had values for the three axes: Nx equal to 25.7 cm; Ny equal to 23.2 cm and Nz equal to 24.9 cm. Besagni and Inzoli (2017) reported that when using CDF, it is necessary to know the turbulence behavior of water-fertilizer mixture and understand its influence on injector performance. Figure 2 shows a turbulence model for M15. The Edge 1 means the entrance at the conic inlet of the injector, Edge 2 the inlet suction port of water-fertilizers coming from the tank and Edge 3 the Venturi throat, which leads to the Venturi outlet.

Table 3 shows an example of the criteria stablished in the simulations. In this figure, the results are specific for M15 model.

Table 3. Example of data, which were the criteria taken in to account in the various simulations.

Name	Current Value	Progress	Criterion	Comment
GG Av Density (Fluid) 1	991.518 kg/m^3	Archieved (IT = 50)	0.812045 kg/m^3	Checking criteria
GG Av Velocity 1	2.79386 m/s	Archieved (IT = 40)	0.0228009 m/s	Checking criteria
PG Density (Fluid) 1	989.513 kg/m^3	Archieved (IT = 50)	1.08439 kg/m^3	Checking criteria
PG Mass Fraction of Solution	6.42661e-007	Archieved (IT = 74)	7.70023e-007	Checking criteria
PG Temperature (Fluid) 1	44.9998 °C	Archieved (IT = 50)	3.36294 °C	Checking criteria
PG Velocity 1	2.34226 m/s	Archieved (IT = 50)	0.138936 m/s	Checking criteria
PG Volume Fraction of Water	0.999999	Archieved (IT = 74)	6.98861e-007	Checking criteria

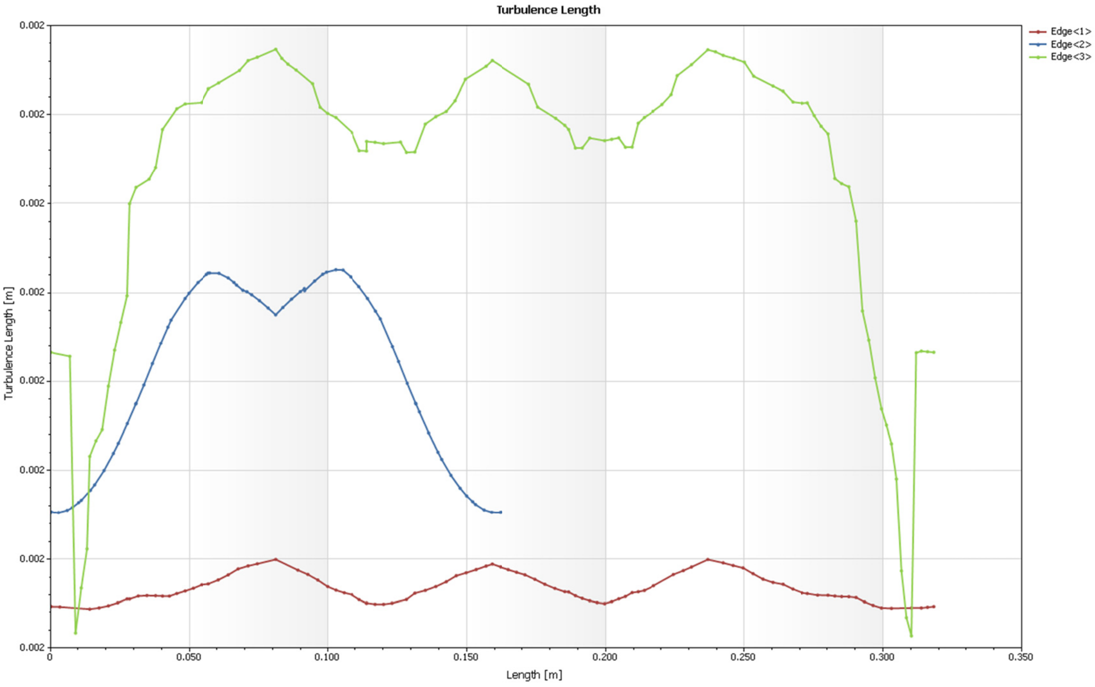


Figure 2. Turbulence model for M15 prototype

To perform the analysis of variance, 1000 iterations for each simulation for each of the 20 prototypes were run. As result, this statistic analysis provided four prototype models, which showed significantly higher values for outlet flow velocity ($\alpha = 0.05$).

Next, the four prototypes that demonstrated the highest efficiency in the simulation were selected, taking into account the speed developed at the exit of the device as a parameter, since it is directly correlated with flow rate and pressure. The experiment was continued using these four prototype models and the rest were discarded.

The simulations were run again with the four selected models using the same CFD software. During this phase, it was included characteristics of the fertilizer-water solutions in the simulations, including density, viscosity and temperature, which can be manipulated for these injector prototypes, and adapted for field irrigation using low-pressure gated irrigation systems.

Therefore, three mixtures of chemical fertilizers having different solutions were prepared. These mixtures fertilizer-water solutions were used and defined according to Palma-López et al. (2002a) and by producers in the study site (Table 4).

Table 4. Water-fertilizer solutions according to Palma-Lopez et al. (2002) and by producers in the study site to be used in the injector prototypes simulations.

Solution	**Urea (Kg)**	**Triple-17 (Kg)**	**Water (L)**
S1	0.063	0.196	1
S2	0.090	0.245	1
S3	0.108	0.318	1

The fertilizer solutions were analysed in a laboratory for density, viscosity and temperature, which influence injector operation (Yuan, Choi, Waller, & Colaizzi, 2000). The results of this analysis were used to provide the data to simulate mixtures of chemical fertilizer dissolved in water. The inclusion of these variables in simulations enabled an *a posteriori* comparison, the efficiency among the four prototype injectors in contrast to fertilizer solutions with the pure water control.

In the simulations, its included temperatures recorded over the last 30 years at station Actopan Clave Clicom 30003, which is located near where validation of the prototype of the Venturi-type injector was performed. Temperature records oscillated within a range of 5 to 43.5 °C (CONAGUA, 2016). Simulations were performed at intervals of 5 °C, beginning at 15 °C. Temperatures between 5 and 10 °C were discarded as they were considered extreme values for the region and with low probability of occurrence. Temperatures for fertilizer solutions at the suction inlet port were considered for simulations including 15, 20, 25, 30, 35, 40 and 45 °C.

At the temperatures mentioned, simulations for each of the four selected injectors were made, for each of which was made three solutions of fertilizer and water with different concentrations of urea and Triple-17 by RALIGREEN ™, México (Table 4), with pure water as a control. These simulations included suction of the fertilizer doses with their corresponding properties in solution at inlet ports for fertilizer-water solutions in the models. A total of 112 simulation tests were performed with the four prototype models selected, with 28 tests for each model, seven temperature levels, four levels of fertilizer concentration, and controls (pure water, no fertilizers). Tests of the prototype models should reveal which model produced significantly higher fluid velocity at the outlet.

Stages 4 and 5: Analysis of the resulting simulation data, and statistical conclusions. Results from all simulations provided a data set of fluid velocities at the outlet. The CFD simulations use a numerical method. This was used to determine the average fluid velocity at the injector outlet.

To statistically evaluate the performance of the four injector's models, a nested factorial arrangement in a completely randomized experimental design was used. The factors evaluated were: 1) The models selected from stage three, with four levels (M2, M11, M14 and M15); 2) The temperature of the solutions with seven levels (15, 20, 25, 30, 35, 40 and 45 °C); and 3) fertilizer solutions, including the control, with a total of four levels (S1, S2, S3 and pure water). The combination of levels of the three factors resulted in 112 different treatment combinations, with 1000 iterations for each simulation for these tests. Given that solutions were included in the simulations, the prototype providing a significantly greater mean value for fluid velocity at the injector outlet was selected. The selection was accomplished using a comparison of means; subsequent to an analysis of variance on the fluid velocities at the injector outlets obtained from the prototype simulations. This ANOVA was designed with a confidence interval (C.I.) of 95 %. Statistical analyses were performed using Statistica® V10 software by Statsoft ™.

Stage 6: Once an injector model was selected that showed the greatest efficiency in the simulations, we proceeded with its construction. The prototype was made to scale using hydraulic Poly Vinyl Chloride (PVC) pipes and fittings, fiberglass and polyester resins for moulding, and to hold the pieces together and support the hydraulic pressure.

3. Results

Stage 2: Design and evaluation of the 20 prototypes. For the prototype design, the real conditions involved were hydraulic pressure in the multi-gated low-pressure irrigation system of 0.7 kg/cm^2 and an irrigation system flow rate of 35 l/s ("El Manzano" project). The above parameters were used to design the injector prototype, from which 20 prototype injectors were modelled (Table 5). For its calculation, equations 1-5 were used. Figure 3 shows a prototype fertilizer injector modelled in 3D.

Table 5. Results of calculated variables for the prototype design used for prototypes in the simulations by SolidWorks FlowSimulator® 2014. All values were a reference values for simulations

Variable	Results
Inlet fertilizer absorption Flow Rate	18 l/min
Income Flow Rate	35 l/s
Outcome Flow Rate	29 l/s
Efficiency	77.5 %
Total pressure rate	1.25
Injection capacity	0.62 l/s

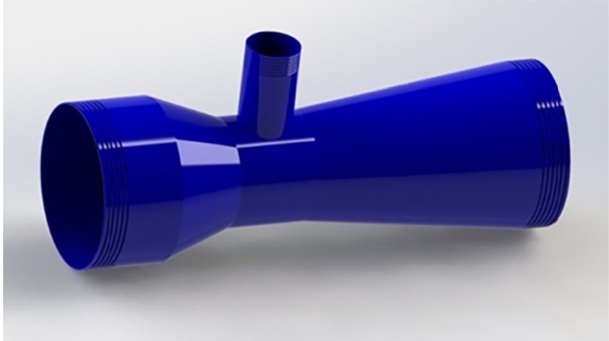
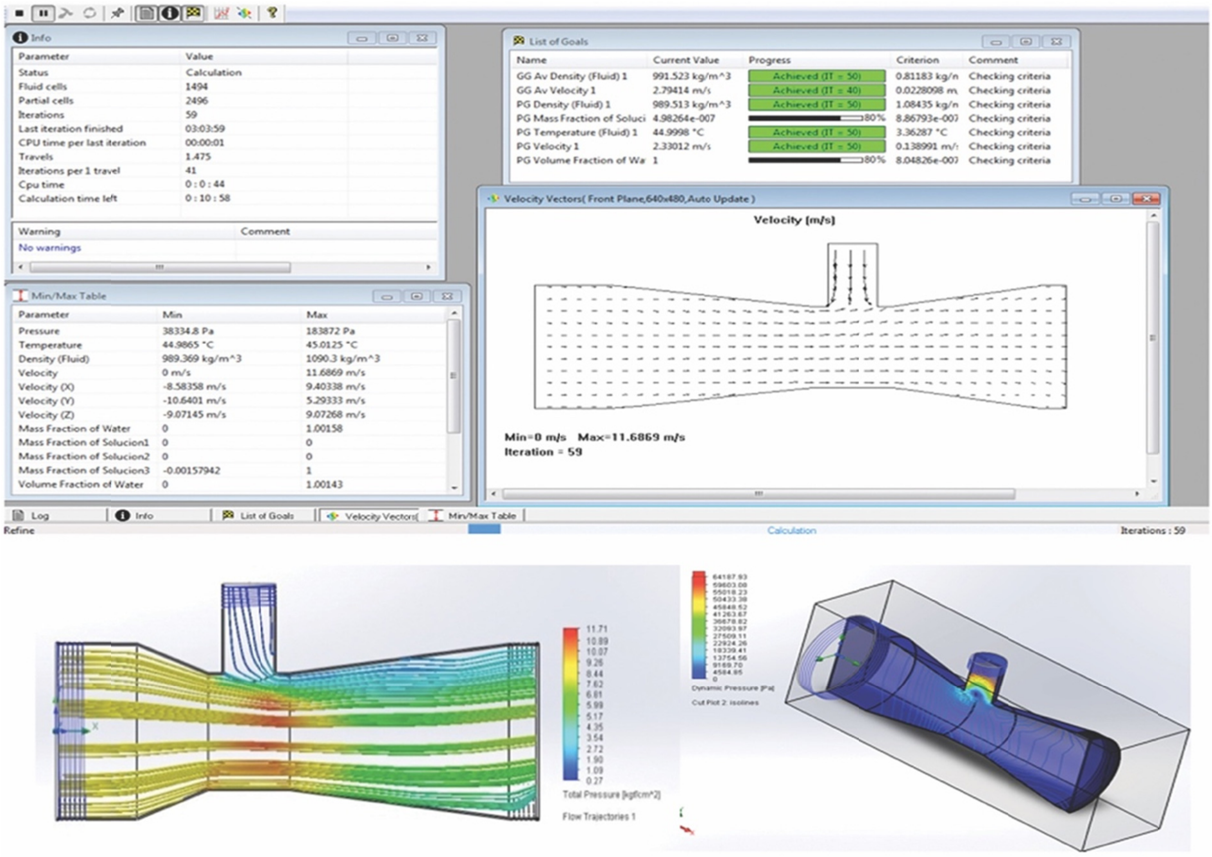


Figure 3. One of prototypes fertilizer injector, modelled in 3D, using the software *Solidworks*® 2014

The Figure 4 shows one of the 20 simulations with which the statistical comparison of means was performed for the fluid outlet velocities developed by each model. As a result of the normality test, the t-test significance was *p value* = 0.05396, suggesting a marginally normal distribution.

Subsequently, the ANOVA of flow rates at the injector outlets resulted in significant differences among the means for the 20 models ($\alpha = 0.05$, F = 3172, *p value* ≤ 2 e^{-16}). Figure 5 displays the means comparisons of the 20 simulated prototype models compared with pure water at an ambient temperature of 20 °C and the multiple means comparisons. Posteriory, a Tukey test, $\alpha = 0.05$ was performance (Table 6). As can be seen, the four models chosen in Stage 3 (M2, M11, M14 and M15) as the prototypes having the best performance regarding fertilizer-water solutions are highlighted in a pure water simulation.



Info

Parameter	Value
Status	Calculation
Fluid cells	1494
Partial cells	2496
Iterations	59
Last iteration finished	03:03:59
CPU time per last iteration	00:00:01
Travels	1.475
Iterations per 1 travel	41
Cpu time	0 : 0 : 44
Calculation time left	0 : 10 : 58

Warning	Comment
No warnings	

List of Goals

Name	Current Value	Progress	Criterion	Comment
GG Av Density (Fluid) 1	991.523 kg/m^3	Achieved (IT = 50)	0.81183 kg/n	Checking criteria
GG Av Velocity 1	2.79414 m/s	Achieved (IT = 40)	0.0228098 m	Checking criteria
PG Density (Fluid) 1	989.513 kg/m^3	Achieved (IT = 50)	1.08435 kg/n	Checking criteria
PG Mass Fraction of Soluci	4.98264e-007	80%	8.86793e-007	Checking criteria
PG Temperature (Fluid) 1	44.9998 °C	Achieved (IT = 50)	3.36287 °C	Checking criteria
PG Velocity 1	2.33012 m/s	Achieved (IT = 50)	0.138991 m/	Checking criteria
PG Volume Fraction of Wa	1	80%	8.04826e-007	Checking criteria

Velocity Vectors(Front Plane,640x480,Auto Update)

Velocity (m/s)

Min=0 m/s Max=11.6869 m/s
Iteration = 59

Min/Max Table

Parameter	Min	Max
Pressure	38334.8 Pa	183872 Pa
Temperature	44.9865 °C	45.0125 °C
Density (Fluid)	989.369 kg/m^3	1090.3 kg/m^3
Velocity	0 m/s	11.6869 m/s
Velocity (X)	-8.58358 m/s	9.40338 m/s
Velocity (Y)	-10.6401 m/s	5.29333 m/s
Velocity (Z)	-9.07145 m/s	9.07268 m/s
Mass Fraction of Water	0	1.00158
Mass Fraction of Solucion1	0	0
Mass Fraction of Solucion2	0	0
Mass Fraction of Solucion3	-0.00157942	1
Volume Fraction of Water	0	1.00143

Figure 4. Functional simulation of a prototype using the software *Solidworks FlowSimulator 2014* ®. The colour differences indicate changes in total pressure rate inside the injector (left-hand image) and changes in dynamic pressure inside the injector (right-hand image)

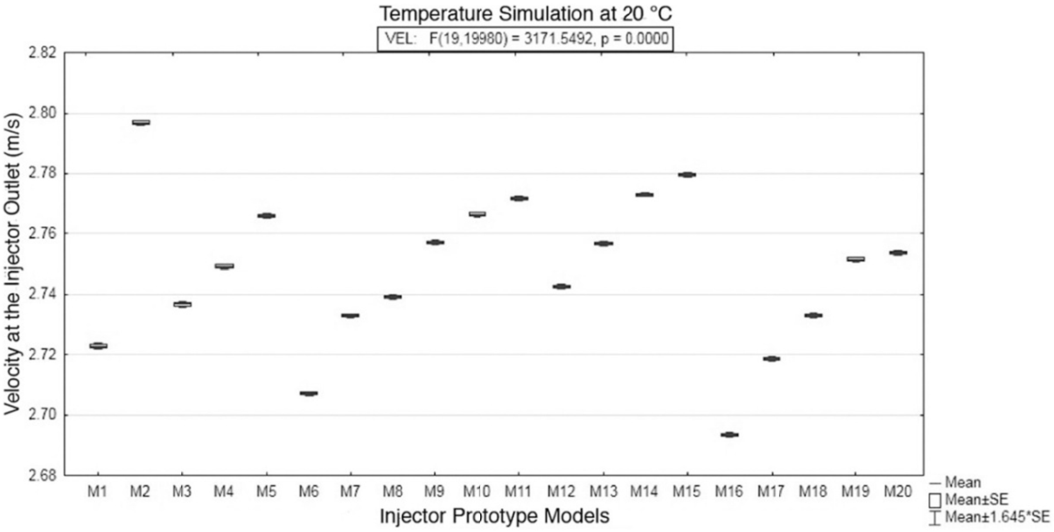


Figure 5. Graphic comparison of the velocity means at the outlet for each of the 20 prototype models simulated with pure water

Table 6. Subgroups of model prototype fertilizer injectors according to their simulated mean outlet water velocities (Tukey HSD-test, α = 0.05)

Model	**Means**	**Groups of Models**
M2	2.796891	A
M15	2.779598	B
M14	2.772825	C
M11	2.771627	C
M10	2.766393	D
M5	2.765823	D
M9	2.757221	E
M13	2.756660	E
M20	2.753696	F
M19	2.751474	Fg
M4	2.749231	G
M12	2.742583	H
M8	2.739102	I
M3	2.736710	J
M18	2.733090	K
M7	2.732917	K

Stage 3: Simulated performance of the four prototypes including solutions and temperatures selected. The fertilizer mixtures suggested by the producers, and tested by Palma-López et al. (2002b), are shown in Table 7; equivalent solutions were then obtained for the fertilizer-water mixtures (Table 4). Based on laboratory analyses of these solutions, are obtained the results shown in Table 8, in which the calculated values of solution densities are included. Viscosity was also considered, which is automatically calculated by *SolidWorks FlowSimulator*® 2014 software for the density and salinity data.

Table 7. Solution dosses recommended for fertilizer applications per hectare per year in sugarcane for fertigation used in simulations (Palma-López et al., 2002)

Dosses	**N (kg)**	**PO (kg)**	**KO (kg)**	**H_2O (L)**
D1	150	80	80	800
D2	200	80	80	800
D3	250	80	80	800

Table 8. Calculated densities for the fertilizer solutions based on the mean densities used in the simulations. ppm it means part per million

T (°C)	**Mean Salinity (ppm)**			**Calculated Density (g/cm^{-3})**		
	S1	S2	S3	S1	S2	S3
15	92.4	96.0	103.0	1.0992	1.0992	1.0992
20	91.4	93.0	100.0	1.0983	1.0983	1.0983
25	90.0	95.0	115.6	1.0971	1.0971	1.0971
30	79.5	103.9	113.8	1.0957	1.0957	1.0957
35	74.0	99.0	113.4	1.0941	1.0941	1.0941
40	67.0	100.0	111.7	1.0923	1.0923	1.0923
45	62.0	97.0	109.5	1.0902	1.0903	1.0903

Effects from interactions among factors also were tested. The Multivariate analysis revealed significant differences for the treatment factor *Solutions* (α = 0.05), but not for the factors *Models* and *Temperature*. Therefore, an α = 0.01 adjust was maded. Whit this α, significant differences were observed for *Models* and *Temperature* (Table 9). *Solutions* factor presented no significant difference with C.I. of 99 %. When comparing treatments, the highest values for flow velocity at the injector outlet were found with increased performance in M15 at 45 °C (Figure 6).

Table 9. Multivariate analysis results from the factorial experiment using the factors Models, Temperature and Solutions ($\alpha = 0.01$). Red are significant results.

Source variation	**Sum squares**	**DF**	**Mean squares**	**F value**	***p* value**	**Observed power ($\alpha = 0.01$)**
Intercept	846.2466	1	846.24	$2.67\ E^{+09}$	$0.00\ E^{-01}$	1.00
Models	0.1752	3	0.05	$1.84\ E^{+05}$	$0.00\ E^{-01}$	1.00
Temperature	$1.01\ E^{-05}$	6	$1.68\ E^{-06}$	5.30	$0.88\ E^{-06}$	0.96
Solutions	$2.85\ E^{-06}$	3	$9.49\ E^{-07}$	2.99	0.034	0.44
Error	$3.13\ E^{-05}$	99	$3.16\ E^{-07}$			

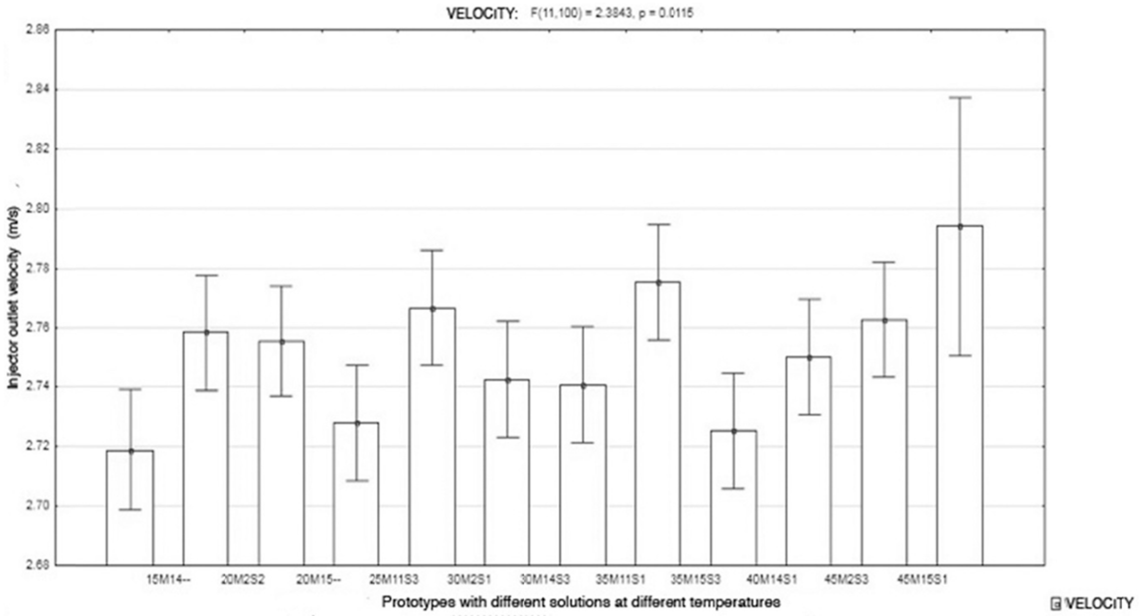


Figure 6. Means comparison of flow velocities at the prototype outlets using different solutions at different temperatures. Along the x-axis, for column code, the first two numbers represent temperature, followed by the letter M and numbers that identify the model, followed by the letter S and a number referencing the solution type (- indicates water). The bars indicate the minimum significant difference among prototypes

To select the injector model, mean values for fluid velocities of prototypes M2, M11, M14 and M15 were graphed. These were tested with all three doses of fertilizer and pure water at 20 °C. A Tukey means comparison test was performed only for *Models* to determine statistically significant differences among levels, and temperature was considered as a non-controllable factor in open agriculture. Table 10 presents the final results for the selection of the prototype fertilizer injector. These same results are shown graphically in Figure 7, where model M15 stands out from the others regarding greater fluid velocity at the injector outlet at 35 °C.

Table 10. Tukey HSD-test; $\alpha = 0.01$ on the factor Models. Velocities occurring at the outlets of the fertilizer injector prototypes are generated by simulations which used the variables solution density and solution viscosity at 20 °C.

Model	**Group of Models**	**Mean (m/s)**	**Standard deviation (m/s)**
M15	A	2.2788	0.0769
M14	B	2.1912	0.1144
M11	C	2.1049	0.0759
M2	D	2.3440	0.0450

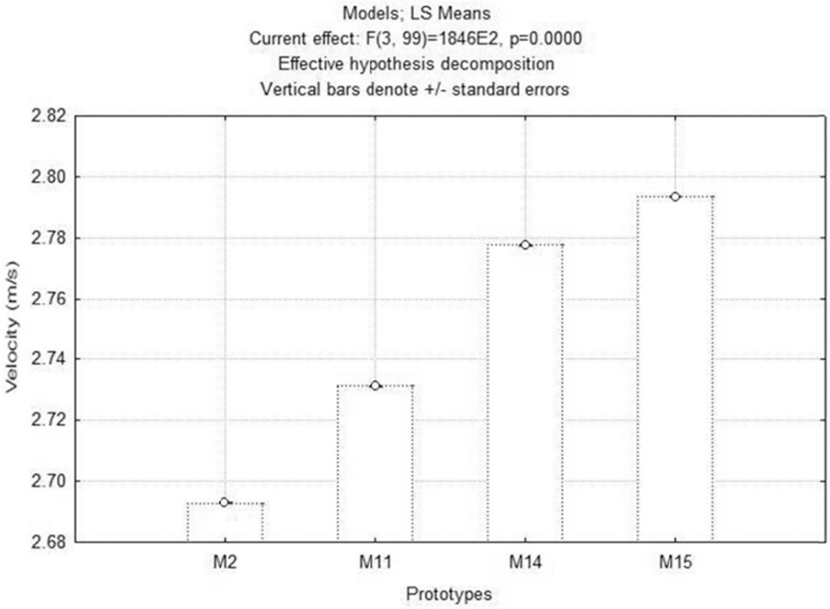


Figure 7. Final results for the selection of injector prototype models based on fertilizer solution, density and temperature (α = 0.01). Model M15 shows a velocity significantly greater at the injector outlet (2.7940 m/s) at 35 °C

4. Discussion

The most important hydraulic factors in designing an efficient Venturi-type fertilizer injector are the convergent and divergent angles, the diameter ratio (d/D, the ratio between the throat diameter [d] and injector inlet diameter [D], called β), and the throat diameter. The diameter of the suction port controls the suction velocity for the fertilizer and the amount of fertilizer absorbed if it is connected to a flow control valve that restricts the flow, thus controlling mixture homogeneity at the injector outlet. Similar works have been found in literature but the main difference between such studies and the presented herein is the size of the analysed injectors.

In the past, high performance Venturi-type injectors have been tested using convergent angles (θc) of 10.5 and 21° (Reader-Harris et al., 2001), and divergent angles (θd) of 5 and 7° (Manzano et al., 2016; Zárate, 1995a). With the results of this research, its confirms that Venturi-type injectors with θc = 21° and θd = 7°, like M2, also works well in multi-gated low-pressure irrigation systems. In Table 1 it can be seen that the M15 model, which showed better performance in the simulation tests with the characteristics of the fertilizer solutions, was designed with a convergent and divergent angle of θc = 7.5º and θd = 10º. In addition to achieving the best performance, it showed significantly higher velocity at the injector outlet. Similar data were used by Huang, Li, and Wang (2008), who obtained the inlet and outlet diameters of the injector equal to 152.4 mm and a throat diameter of 76.2 mm.

The results of the prototype selection using simulations, like this research, agrees with Zárate (1995a) who mentioned that for commercial Venturi-type injectors, θc = 7.5° improves the efficiency of the injector compared to θd = 5° and 7°. Thus, designing a fertilizer injector to meet a particular need may offer better results than buying them.

One of the advantages mentioned by Vargas et al. (2008a) is that Venturi-type injectors can be fabricated with easily accessible materials, such as the PVC tubes, polyester resins and fiberglass used in the present study. As well, such injectors for multi-gated irrigation systems can be designed based on the conditions present in a study area (*e.g.*, a pressure head of).

Moreover, considering the results obtained in this research, it is necessary to include the fertilizer-water concentrations intended for study with the injector in the CFD simulations, and not only pure water. This necessity occurs because of variation in injector performance due to temperature change and solution density (Yuan et al., 2000). Baylar et al. (2009) mentioned that with a minimum pressure difference, the system hydraulic head would generate suction.

In multi-gated irrigation systems, there is sufficient pressure difference to ensure injector proper function. The injector will be then evaluated in the field without the presence of cavitation inside the injector (Yan, Chen, Xu,

& Wang, 2013b), which can occur when the system pressure for field tests is less than 2 kg/cm^2. If this situation were to affect the injector, it would be necessary to control the hydraulic pressure head at the inlet of the injector using a pressure-regulating valve (Kuldeep & Saharan, 2016).

4 Conclusions

The designed prototypes were evaluated, through CFD, in two stages: the first 20 with pure water and the four most efficient, due to their structural characteristics, with the properties of the water-fertilizer mixtures. After of the simulations, the characteristics or structural parameters of the injector with which that was designed and showed better performance were: inlet and outlet diameters of 152.4 mm, a throat diameter of 76.2 mm, a fertilizer suction port diameter of 50.8 mm, and convergent and divergent angles of θc = 7.5° and θd = 10°.

Hydraulic factors, such as convergent and divergent angles, diameters of inlet, outlet and throat, and pressure head, influence injector design. The convergent angles (θc) of 7.5° and 21°, which were already tested in Venturi-type injectors for drip irrigation systems, also work for injectors in multi-gated irrigation systems. The convergent angle of 16°, proposed for the design of the prototype injector in the present study, did not exceed the performance of the aforementioned angles.

In the simulation process used in the present study, the designed M15 prototype injector developed a constant outlet velocity of 2.79 m/s, ensuring uniform application of the fertilizer-water solution. This was achieved by designing and modelling the device in 3D using the CFD software, which must include all fluid physical properties, particularly density, viscosity and temperature, which significantly influence the final results.

In the review of literature carried out, there was little information on fertilizer application devices using the principle of the Venturi tube in low-pressure multi-gated irrigation systems. There are little information about this kind of systems (Mokhtari Hesari, Rezaei, & Shabanali Fami, 2020). So, it is important to develop a prototype that meets the needs for these irrigation systems to save water resources. None of the Venturi-type injector designs previously made has been used in multigate irrigation systems. In most cases, these injectors are used in drip irrigation systems, where the pressure is greater than that required in multi-gated systems, and the dimensions of the injectors and pipes are very small.

The Venturi type injector designed herein will be tested and validated at field scale in another research stage, which has been started in this year. It is therefore clear that the present study corresponds to the first research stage of this project. The results that are to be obtain from the second research stage will be published in due time.

Acknowledgements

This work was supported by Colegio de Postgraduados (COLPOS) and Consejo Nacional de Ciencia y Tecnología (CONACYT), México. Thanks are also due to The Research Line (LGAC) on Agroecosystems, Natural Environment and Climate Change. To Cesáreo Landeros Sánchez, In Memory.

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