

SUMMARY OF THE LIQUID-GAS EJECTOR HYDRAULIC BEHAVIOR – THEORY AND PRACTICE

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Abstract

Liquid-gas ejectors (LGEs) are fascinating devices that use the kinetic energy of the liquid jet to entrain and eventually compress the gas. LGEs find applications in both industry and everyday life, e.g., as sprayers. However, a complex and reliable method for LGE design was not available in the open literature until recently. This contribution follows up on our recent works about the hydraulic behavior of LGE with undisturbed and destabilized liquid jets. This paper aims to summarize the device's complicated hydraulics and characterize its optimal design for three industrially relevant applications - (a) LGE as the vacuum pump, (b) LGE as the gas purification equipment, and (c) LGE as the gas distributor for bioreactors.

Keywords: liquid-gas ejector, jet pump, design method.

1 Introduction

Liquid-gas ejector (LGE) is a technologically simple device that utilizes a high-pressure liquid to entrain and compress a gas. The gas pumping is linked up with the intensive contact of both phases and the fine liquid-gas dispersion with an enormous interfacial area. Therefore, the LGE finds application in the chemical industry, e. g., as a gas distributor in fermentors or as a device for intensive waste gas purification. Even though the LGE has superior mass transfer properties and many publications about hydraulic and mass transfer behavior exist, there is no comprehensive, reliable overview of the LGE design process in the open literature. Therefore, this work focused on summarizing knowledge about LGE and conducting small case studies on LGE design for several specific industrial applications. This work is based mainly on our previous research aimed at the hydraulic behavior of LGE and the possibilities of increasing the gas entrainment rate [1, 2].

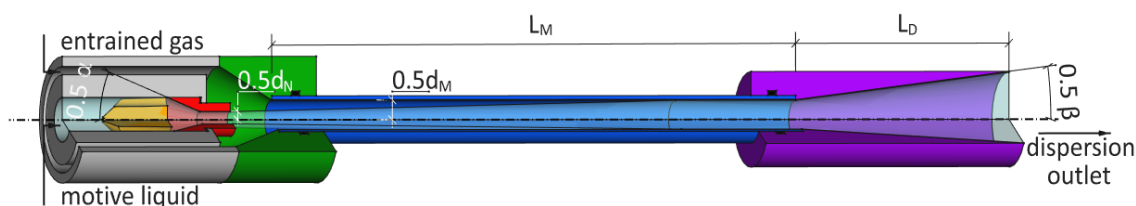


Figure 1: Sketh of the ordinary LGE with marked dimensions and color separated parts: orange - swirl, green - suction chamber with convergent part, blue - mixing tube, purple - diffuser.

Typical LGE consists of (i) the nozzle, (ii) the suction chamber with the convergent part, (iii) the mixing tube, and (iv) the diffuser. The liquid as a motive fluid is fed on the nozzle, its pressure energy is transformed into the kinetic one, and the high-velocity liquid jet exiting the nozzle enters the suction chamber. During the passage of the liquid jet through the suction chamber, the convergent part, and the mixing tube, there is a contact between the phases resulting in the entrainment of the surrounding gas. In the mixing tube, a so-called mixing shock takes place, and the co-current flow of the liquid and gas changes to the bubble flow. The dispersion continues to the diffuser and out of the LGE. This simple type of LGE typically uses a convergent nozzle that produces a coherent, undisturbed liquid jet. The advantage of this basic configuration is a higher value of volumetric mass transfer coefficient $k_L a$ and specific interfacial area a compared

to configurations with destabilized liquid jet [3], which can be an advantage, e. g., for waste gas purification. For such cases, the simple correlation,

$$\dot{m}_G = 3 \times 10^{-4} P_L^{0.75} \Delta p_{DS}^{-0.30} \rho_{G,S} , \quad (1)$$

derived and validated by Haidl et al. [1] against several authors can be used to estimate the safe minimal gas entrainment rate $\dot{m}_G$.

However, in applications where it is necessary to process a large amount of gas with the least possible expenses, the wider deployment of LGEs is hindered by their poor energy efficiency (3%-25%),

$$\eta_{\text{pump}} = \frac{P_G}{P_L} = \frac{\dot{m}_G}{M_G P_L} RT \ln \frac{p_D + p_{\text{atm}}}{p_S + p_{\text{atm}}} . \quad (2)$$

Therefore, in the following work, the possibilities of energy efficiency enhancement were sought [2]. Based on this work, the destabilization of the liquid jet by the swirl in front of the nozzle appears to be a sufficient method, which increases the amount of gas entrainment rate and hence the energy efficiency 2-3 times. The swirl is a special element that spins up the liquid jet and causes it to break up faster in the mixing tube due to centrifugal force. To quantify the swirl's ability to spin the liquid jet, the swirl number,

$$Sw = \frac{2G_{\text{rad}}}{dG_{\text{ax}}} , \quad (3)$$

which relates the angular momentum flux to the axial momentum flux, can be used. To predict the gas entrainment rate and the energy efficiency of the optimal LGE with destabilized liquid jet, a semi-empirical model was derived:

$$\dot{m}_G = \frac{\pi}{4} (v_M^{\circ} d_M^2 - v_N d_N^2) \left[1 - \sqrt{\frac{\Delta p_{DS}}{\Delta p_{DS}^{\circ}}} \right] \sqrt{\rho_{G,D} \rho_{G,S}} , \quad (4)$$

$$v_M^{\circ} = \sqrt{v_N^2 + 2gL_H \sin \psi} - \Delta v_M^{\circ} , \quad (5)$$

$$\Delta p_{DS}^{\circ} = p_D - p_S = \frac{1}{2} \rho_L v_N^2 \left\{ 1 - \left[1 - \left(\frac{d_N}{d_M} \right)^2 \right]^2 \right\} + gL_H \rho_L \sin \psi . \quad (6)$$

The empirical part of the model comprises two fitted parameters in the so-called slip velocity term, $\Delta v_M^{\circ} \approx 0.25 \left(\frac{d_M}{d_N} \right)^3$. Whilst Eq. (1) predicts the minimal gas entrainment rate of a coherent jet LGE, this model describes the maximum amount of gas entrained by an optimal geometry LGE with a destabilized jet.

Together, the presented methods of gas entrainment rate estimation for LGE with a coherent and destabilized jet provide a reliable basis for the design of liquid-gas ejectors. In this contribution, these are used as a tool for the design of an optimal LGE employed in three different industrial applications.

2 Case studies

In the following subsections, possible procedures of the LGE design for three different applications will be presented. The first case will focus on the design of a vacuum pump for creating a relatively high vacuum, e.g., in distillation columns or desalination plants [4]. The second study will focus on the ejector design for cleaning waste gas from relatively small solid particles [5]. The third case will simulate the LGE design for fermenter aeration, for example, in wastewater treatment [4, 6].

The following simplifying assumptions were introduced in the calculations (for simple illustration). The ideal gas law EOS is exclusively used for the conversion of all state variables. Normal volume units (e.g, N m³) are given at the absolute temperature of 273.15 K and the absolute pressure of 1 bar. Gas and liquid are approximated by the air and water, and their densities are

calculated at an assumed absolute temperature of 283.15 K. Bernoulli's law is used to relate velocity and pressure along the streamlines, and the fluid velocity in the feeder in front of the nozzle is assumed to be zero ($d_0 \gg d_N$).

When calculating liquid-gas ejectors, we probably encounter the following case most often. We know at what pressure difference $\Delta p_{DS} = p_D - p_S$ the LGE has to work (gas compression) and what amount of gas $\dot{m}_G$ we need to transport (gas flow rate). In the case of the coherent jet LGE, it is recommended to use Eq. (1). From Eq. (1) we can express the liquid power input,

$$P_L = \dot{m}_L \left(\frac{v_0^2}{2} + \frac{p_0 - p_S}{\rho_L} \right) \approx \dot{m}_L \frac{p_0 - p_S}{\rho_L}, \quad (7)$$

required for gas suction and compression. Then, from Eq. (7), Bernoulli's law, and continuity equation, we can express the v_N or d_N parameter and optimize the second one. With the known nozzle diameter d_N , we can then easily calculate the mixing tube diameter d_M and length L_M according to the recommended ranges in [1].

If it is desirable to increase the energy efficiency η_{pump} of the device, it is possible to design an LGE with a destabilized jet according to Eqs. (4–6). If the situation allows, we use a convergent nozzle and a swirl for destabilization. In these cases, we proceed similarly to the LGE with a coherent jet - we optimize the v_N and d_N parameters with respect to the required amount of sucked gas and the pressure difference. The mixing tube diameter d_M and length L_M , and the swirl number Sw we choose according to the planned use of LGE and recommended ranges in [2].

2.1 Vacuum pump

One of the most common uses of the LGE is a laboratory vacuum pump, e. g., for vacuum filtration. The bigger LGE units are utilized in industrial vacuum processes, typically as vacuum generators on the evaporators or distillation columns. In these applications, the intensive contact of gas/vapor and liquid phase is leveraged, enabling instantaneous off-gas cooling and washing. Since the ejector does not need electricity to run, it is safe to use even in environments with a high risk of explosion. This case study will be focused on the LGE design for extracting vapors from the vacuum evaporator. It is necessary to maintain the absolute pressure in the evaporator head at 20 kPa and suck up 1.5 g/s of the inert gas, potentially polluted with VOCs. Two LGE variants are presented for comparison; *variant 1* using a coherent liquid jet designed according to [1] and *variant 2* using a jet destabilized by means of the swirl designed according to [2]. Tab. (1) summarizes the inputs and (intermediate) results of both design procedures.

Table 1: Summarization of vacuum pump design procedure inputs and (intermediate) results for both variants.

Parameter	Unit	Variant 1 [1]	Variant 2 [2]
$\dot{m}_G$	g/s		1.5
p_S	kPa		20
p_D	kPa		110
n_{LGE}	(-)		1
d_N	mm	34	16
d_M/d_N	(-)	2.0	2.0
L_M/d_M	(-)	25	40
Sw	(-)	(-)	0.10
P_L	kW	5.3	1.6
η_{pump}	%	7.6	16.8

In Fig. (2) there is a gas entrainment rate progress visualization for coherent (*variant 1*) and destabilized (*variant 2*) liquid jet LGEs depending on the P_L . It is evident, that the LGE with destabilized jet achieves the required $\dot{m}_G$ already at the power input of 1.6 kW, while LGE with the coherent liquid jet is up to 5.3 kW. This also corresponds to the energy efficiency η_{pump} of both variants, calculated from Eq. (2), where *variant 2* reaches $\eta_{\text{pump}} = 16.8\%$ compared to 7.6% for

variant 1. In this case, the *variant 2* is the better choice due to the lower operating and acquisition costs.

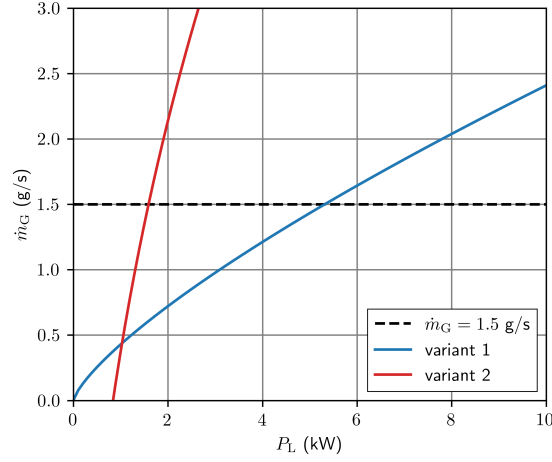


Figure 2: Dependence of gas entrainment rates, $\dot{m}_G$, on the liquid power input, P_L , for two variants of LGEs designed for vacuum evaporator.

2.2 Waste gas purification

Due to the great value of the specific interfacial area [3], LGE finds application in the purification of waste gases problematics. The assignment of this study is based on a real industrial project, which was elaborated on by Linek et al. [5] in 2018. The task is to design an ejector with a bubble column that will be able to capture fine solid particles from the gas into the circulating wash water. The waste gas flow rate swings around $0.2 \text{ N m}^3/\text{s}$, and the pressure difference is only 3 kPa. Three solutions are proposed to solve this problem. In *variant 1*, the single LGE ($n_{\text{LGE}} = 1$) uses a coherent liquid jet. *Variant 2* deals with the ejector battery, where twenty smaller coherent jet LGEs are in parallel ordering ($n_{\text{LGE}} = 20$). Case study *variant 3* utilizes the single destabilized jet LGE with the swirl. The first two variants are designed according to Haidl et al. [1]. The third variant uses the hydraulic model for the LGE with destabilized jet by Gebouský et al. [2]. Tab. (2) summarizes the inputs and (intermediate) results of all three designated variants.

Table 2: Summarization of waste gas purification design procedure inputs and (intermediate) results for all variants.

Parameter	Unit	Variant 1 [1]	Variant 2 [1]	Variant 3 [2]
Q_G	$\text{N m}^3/\text{s}$		0.2	
p_S	kPa		100	
p_D	kPa		103	
n_{LGE}	(-)	1	20	1
d_N	mm	219	30	63
d_M/d_N	(-)	2.0	2.0	3.5
L_M/d_M	(-)	20	20	30
Sw	(-)	(-)	(-)	0.13
P_L	kW	150.3	55.3	12.6
η_{pump}	%	0.4	1.1	4.9

Fig. (3) shows the dependencies of the gas flow rate Q_G on the liquid power input P_L . It is clear that the single ejector with the coherent jet absolutely cannot compete with the second and third options. The large nozzle diameter d_N of 219 mm in *variant 1*, in addition, causes a proportional enlargement of the mixing tube and the diffuser so that even the acquisition costs of such an LGE

would be unbearably high. *Variant 3*, which uses single LGE and swirl, appears to be the best in terms of operating costs and device size. However, if the swirl ejector is not capable of creating a fine enough dispersion to capture solid particles (see Introduction or [3]), a middle way could be a unit consisting of 20 parallel ejectors with the nozzle diameter of 30 mm (*variant 2*).

From the point of view of energy demands, it is interesting to observe that while in the previous application with a large pressure difference (vacuum pump) the efficiency of the best device was around 17%, in this case, the efficiency of *variant 3* does not reach above 5%. It can be stated that with a decreasing pressure difference, and therefore less gas compression, the energy efficiency of LGE decreases, which also results from the conclusions of the works [1, 2].

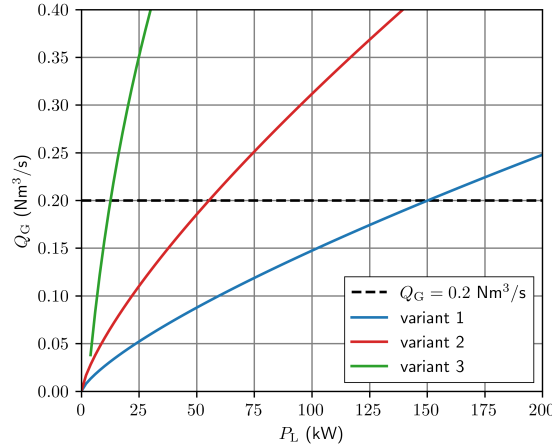


Figure 3: Dependence of gas entrainment rates, Q_G , on the liquid power input, P_L , for three variants of LGEs designed for waste gas purification.

2.3 Fermentor gas distributor

In the last case study, the LGE is assumed as a gas distributor for various bioreactors [6]. Process batch serves as the motive liquid, which recirculates in a loop with LGE and entrains the air (or oxygen). The gas is compressed and blown into the fermentor in a fine dispersion. Also, the LGE itself saturates the liquid, and strongly turbulent flow supports mixing and thus the transport processes in the batch. Despite the apparently harsh environment and expected high shear stress resulting from broth pumping and contraction in the nozzle, the cell cultures are not excessively damaged in LGE. In fact, its utilization has been found superior to the conventional stirred tank reactors [6].

For the LGE design demonstration, we will use a model square vessel $5\text{ m} \times 5\text{ m} \times 3\text{ m}$, which is used for activated sludge aeration in wastewater treatment. The process requires homogeneous air distribution across the vessel area and an aeration rate of $0.4\text{ N dm}^3/(\text{m}_{\text{sludge}}^3\text{ s})$. The air has to be compressed from the atmospheric pressure of 1 bar to the vessel bottom with a static pressure of 1.3 bar. The potential blockage of the feed by sludge excludes the swirl use, hence the LGE will be designed either according to [1] with the coherent liquid jet or according to [2] with the jet destabilized by means of the orifice nozzle. In the first and third case, 5 parallel LGEs will be used ($n_{\text{LGE}} = 5$, 1 LGE per 5 m^2). Unit in the second variant consists of $n_{\text{LGE}} = 25$, which corresponds to 1 LGE per m^2 . *Variant 3* is a special case of liquid jet destabilization. Due to the steep change of the diameter along the nozzle, flow separation occurs, and the exiting jet has a smaller diameter (and thus a higher velocity than expected). Therefore, the empirical correction of the d_N is used to calculate such an ejector. More information on the design of the high pressure-loss orifice nozzle ejector can be found in Gebouský et al. [2].

Fig. (4) shows the dependence of aeration rates on the liquid power input P_L . *Variants 1*, and *2* use variously parallelized units. It can be seen the improvement in energy efficiency and gas entrainment rate again with the increasing parallelization. The destabilized jet LGE unit (*variant 3*) is the best in energy demands terms.

Table 3: Summarization of fermentor aerator design procedure inputs and (intermediate) results for all variants.

Parameter	Unit	Variant 1 [1]	Variant 2 [1]	Variant 3 [2]
$AerationRatio$	$N \text{ dm}^3 / (\text{m}^3_{\text{sludge}} \text{ s})$		0.4	
p_S	kPa		100	
p_D	kPa		130	
n_{LGE}	(-)	5	25	5
d_N	mm	33	11	16
d_M/d_N	(-)		2.0	3.0
L_M/d_M	(-)		30	40
Sw	(-)		(-)	orifice nozzle
P_L	kW	17.6	10.3	5.7
η_{pump}	%	4.6	7.9	14.3

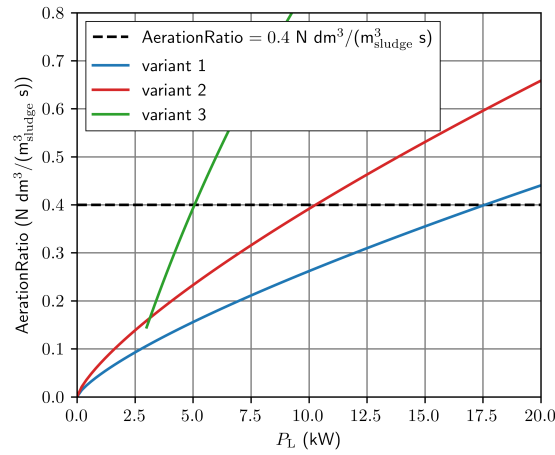


Figure 4: Dependence of aeration rate on the liquid power input, P_L , for three variants of LGEs designed for active sludge tank aeration.

3 Conclusions

This contribution is focused on the utilization of theoretical hydraulic behavior knowledge about the liquid-gas ejectors in the design of real industrial devices. In the introductory part, the computational hydraulic models of the LGEs with a coherent and destabilized liquid jet are outlined. The second part deals with simple case studies, in which the practical use of the hydraulic models is demonstrated.

The results outline the possibility of using parallel ejector units with a coherent jet, which can significantly improve the efficiency of the entire process. It should be recalled that Eq. (1) provides an estimate of the minimum gas entrainment rate, and the summary of Eqs. (4–6), on the contrary, provides the gas entrainment rate for the absolutely optimal geometry of destabilized jet LGE. These two models, therefore, define a certain working space in which the gas entrainment rate of a realistically built ejector can vary.

Acknowledgment

This work was supported by the grant of *Specific University Research A1-FCHI-2022-004* and by the Institute of Hydrodynamics of the Czech Academy of Sciences.

Nomenclature

Symbols		
a	m^2/m^3	specific interfacial area
d	m	diameter
k_{La}	s^{-1}	volumetric mass transfer coefficient
L	m	length
M	kg/mol	molar mass
$\dot{m}$	kg/s	mass flow rate
n_{LGE}	—	number of LGE devices
P_L	W	water jet power input
p	Pa	pressure
Δp_{DS}	Pa	pressure difference between diffuser outlet and suction chamber
Q	m^3/s	volumetric flow rate
Sw	—	swirl number
T	K	thermodynamic temperature
v	m/s	velocity
η_{pump}	—	pumping efficiency
ρ	kg/m^3	density
σ	—	nozzle loss coefficient
ψ	rad	LGE orientation angle with respect to the horizontal plane
Subscripts		
0	in front of the nozzle	
D	diffuser outlet	
G	gas	
L	liquid	
M	mixing tube	
N	nozzle	
S	suction chamber	

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