Experimental Study on Deliquification with Atomizing Nozzle in Gas Well

Yutang Gao, Xiaobai Li, Peng Chang and Lei Liu *

State Key Laboratory of Multiphase Flow in Power Engineering, Xi’an 710049, Shaanxi, P.R. China
Email: rliu@mail.xjtu.edu.cn

Abstract. Gas is a clean energy resource in comparison with oil and coal. Liquid-loading problem is frequently encountered in the process of gas production. It would directly cause the production of gas wells decreasing, even off production. A number of deliquification techniques have been suggested for solving this kind of problem, but the available techniques are not yet widely applicable. Based on the analysis, the method of deliquification with atomizing nozzle in gas wells was put forward. The test bench was designed for studying the atomization of nozzles and the liquid entrainment of gas flow. The size distribution of atomized droplets was measured by Malvern laser grain size analyzer. The Sauter mean diameters of atomized droplets were analysed under different two-phase flow conditions. The results indicate that the designed nozzles have good atomization performances and show potential application for reducing liquid loading in gas wells.

Keywords. Gas well; liquid loading; deliquification; atomizing nozzle; two-phase flow.

1. Introduction

Natural gas is a clean energy resource in comparison with oil and coal. In the process of the exploitation of gas wells, gas production and flow velocity decrease gradually with the extended exploitation time. It will lead to the decline of liquid entrainment capacity of gas flow, and the inability to entrain the liquid accumulated at the bottom of the well to the wellhead. The loading liquid accumulates to form liquid column, which increases the backpressure of static water in gas reservoir and further reduces the self-blowout energy of the gas well. If this cycle continues, the accumulated liquid column in wellbore rises and eventually blocks up the gas, resulting in the shutdown of gas well [1].

The technology of deliquification is developed because the phenomenon of liquid-loading occurs in gas wells. The technology is an effective mean to eliminate wellbore liquid accumulation in the middle and later stages of gas well exploitation and to improve the recovery rate of liquid-accumulated gas wells. Over the years, in order to exploit gas resources as completely as possible, domestic and foreign gas producers have developed various kinds of deliquification technologies for liquid-loading gas wells [2-4]. At present, the conventional deliquification technologies include gas lift [5], velocity string [6], foam [7], machine [8], electric submersible pump [9], jet pump [10, 11], etc.

As long as the gas velocity is high enough, the bottom-hole liquid-loading can be lifted to the wellhead to prevent the occurrence of fluid accumulation. The theory of critical flow velocity is a relatively simple method for predicting the starting point of liquid-loading in gas wells. Turner et al. [12] originally put forward the critical liquid entrainment model and deduced the critical gas flow velocity to avoid the occurrence of liquid-loading. Coleman et al. [13] pointed out that Turner’s model
is not suitable for those wells with wellhead pressure less than 3.45 MPa. After analyzing the production data of many low-pressure gas wells, they derived the critical flow velocity calculation equation applicable to such gas wells. Nosseir et al. [14] found that Turner’s approach was not comprehensive enough. He adopted different drag coefficient according to the different Reynolds number, and based on the spherical droplet theory, obtained the turbulent flow model under the high-speed turbulent flow state. Li et al. [15] found that small droplets in Turner droplet model may deform under the pressure difference between front and back when they are impacted by high-speed gas flow. They considered the deformed droplets to be a flat ellipsoid and developed relevant derivation. Based on the larger upstream area of the deformed ellipsoid, they deduced a new critical velocity equation.

By changing loading liquid into smaller droplets, gas can carry the liquid out of wellbores more easily. Based on this idea, the research is conducted for the method of gas production by atomizing liquid from nozzles. The flow pattern of two-phase flow in wellbores will become mist flow. The key to the design of deliquification technology is the size of droplets which are atomized after the liquid passes through the atomizing nozzle. If the diameter of droplets is too large, the gas flow will not be able to entrain them to the wellhead and cause droplets to fall back. Therefore, before designing the deliquification tool with atomization method, the maximum droplet size that can be carried by the gas flow in the wellbore should be considered, and the atomizing nozzles should be designed on such basis.

2. Methodology

2.1. Theory on Critical Liquid Entrainment

Up to now, it is believed that the flow pattern in the wellbore is usually mist flow before a large amount of fluid accumulation. The liquid is usually lifted by gas phase in the form of droplets, while near the wellbore wall, the liquid phase slides upward by the way of liquid film driven by the viscous force between the two phases [16, 17].

Turner et al. [12] developed a simple relationship to predict the critical velocity in vertical wells by using droplet model. In this model, droplets are subjected to downward gravity and upward drag. The critical velocity of gas flow entraining liquid in wellbore is defined as the velocity of gas flow when droplets reach suspension and standstill in gas flow. When the velocity of gas flow is lower than the critical velocity, the droplets fall and the wellbore begins to accumulate fluid. When gas velocity becomes higher, the gas flow will entrain the droplets to the surface and eliminate the liquid accumulation in the wellbore.

It is assumed that both gas and droplets flow uniformly in vertical pipe flow. Droplets in gas flow are subjected to upward drag force of surrounding gas and downward gravity force.

The upward drag force is given by

\[ F = \pi d^2 C_d u^2 \rho_g / 8 \]  

The expression of gravity force is

\[ G = \pi d^3 (\rho_l - \rho_g) g / 6 \]  

where \( d \) is the droplet diameter (m); \( C_d \) is the drag coefficient; \( u \) is the flow velocity of gas (m·s\(^{-1}\)); \( \rho_l \) and \( \rho_g \) are densities of liquid and gas, respectively (kg·m\(^{-3}\)).

When \( F - G \geq 0 \), droplets are lifted. Therefore, the critical velocity denoted by \( u_c \) is

\[ u_c = \sqrt[4]{\frac{3 C_d \rho_g}{4 (\rho_l - \rho_g) gd}} \]
Turner et al. [12] believe that as long as the largest diameter droplets in the gas well can be lifted, there will be no liquid-loading in the gas well. The maximum droplet diameter $d_{\text{max}}$ corresponding to the critical velocity can be deduced as

$$
d_{\text{max}} = \frac{3}{4} \left( \frac{\rho_d H_c^2 \rho_s}{\rho_t - \rho_s} \right) g
$$

(4)

2.2. Design of Atomizing Nozzle

The supersonic nozzle is proposed as the atomizing nozzle in the system of deliquification [18]. Supersonic nozzles can produce supersonic jet in the exit area, and the relative velocity between gas and liquid is larger, resulting in stronger aerodynamic interference between high-speed gas flow and surrounding gases. In one-dimensional isentropic flow, the relationship between velocity and cross section is expressed as

$$
\frac{du}{u} = -\frac{1}{Ma^2 - 1} \frac{dA}{A}
$$

(5)

where $u$ is the flow velocity of fluid in nozzle ($\text{m} \cdot \text{s}^{-1}$); $Ma$ is the Mach number; $A$ is the cross-sectional area of nozzle ($\text{m}^2$).

If we expect the flow velocity at the nozzle outlet to reach supersonic speed, the physical structure of the nozzle must satisfy the requirement [19, 20]. The gas flow must be accelerated in the pipe with gradually contracted structure, and then changed to the pipe with gradually expanding structure when the flow velocity reaches the critical state ($Ma = 1$), so that the gas flow can reach supersonic speed. Therefore, the physical structure of supersonic nozzles should be a convergent-divergent structure. The de Laval nozzle can be used as the supersonic atomizing nozzle. The throat diameter of de Laval nozzles tested in the experiment is shown in table 1.

| Throat diameter (mm) | Throat diameter (mm) |
|---------------------|---------------------|
| 1.0                 | 1.6                 |
| 1.2                 | 1.8                 |
| 1.4                 | 2.0                 |

3. Experiment and Measurement

The atomization effects of the supersonic nozzles are very important for the method of deliquification proposed in this paper. The atomization characteristics of these nozzles can be tested by experimental means. In order to test the atomization effects of nozzles and analyze the liquid entraining characteristics of gas flow, a test bench was designed and built for atomization characteristics of nozzles.

3.1. Experimental System and Measurement Equipment

Figure 1 is the schematic of the experimental system. This system mainly includes gas transmission line, liquid transmission line, experimental section after gas-liquid mixing, measurement and display system and other test elements, etc. The Malvern laser grain size analyzer (Spraytec) was used to measure the diameters of atomized droplets after nozzle, and the data were analyzed by Spraytec analysis software. Spraytec grain size measurement system can achieve real-time and online measurement of spray effect, and analyze the droplet size.
1-Spraytec; 2-Test section; 3-Pressure gauge; 4-Ball valve; 5-Orifice flowmeter; 6-Compressor; 7-Computer; 8-Control valve; 9-Back-pressure valve; 10-Meter; 11-Pump; 12-Tank.

**Figure 1.** Schematic of the experimental system.

The basic working process of the experimental apparatus is as follows: liquid working fluid is stored in the tank and transported by a single-screw pump during the experiment; gas phase is supplied by a compressor and enters the gas transmission line after passing through orifice flowmeter; liquid and gas are fully mixed before the experiment section and sprayed after the nozzle in the test section; after the atomization is stabilized, Malvern laser grain size analyzer is used to measure and record the test data.

The measurement system mainly includes flow rate measurement, pressure measurement and atomized droplet diameter measurement. The liquid flow rate is measured by water flow meter, and the flow rate entering the main circuit can be adjusted by bypass system. The gas flow rate is measured by orifice flow meter. A pressure gauge is set before the nozzle to measure the pressure value at the nozzle entrance, to detect and control the pressure ratio between the nozzle entrance and exit.

### 3.2. Measurement and Analysis of Atomized Droplet Size

The spray droplet diameters are measured by Spraytec from the intensity of diffracted beams at different angles through droplets. According to the relevant optical theory, we can deduce the general angular distribution of the diffracted beams after the parallel beams pass through the droplets, and the intensity of the diffracted beams is the same when the droplets with the same volume but different droplet sizes are diffracted. Therefore, the droplet size distribution measured by the system is a volume distribution and is related to the sensitivity of the system.

Spraytec characterizes the statistical results of droplets as volume mean diameter ($d_{43}$ or VMD) and Sauter mean diameter ($d_{32}$ or SMD). The maximum diameter of droplets, which is presented in equation (4), is proportional to Sauter mean diameter [21]. Therefore, the Sauter mean diameters are investigated below.

### 4. Results and Discussion

#### 4.1. Data and Analysis of Atomized Droplet Size

For each nozzle, the set gas flow rate ($Q_g$) is 2602 Nm$^3$·d$^{-1}$, and the gas velocity is approximately 14 m·s$^{-1}$ corresponding to the pipe diameter 50 mm. The pressure in front of nozzle ($P_{in}$) is 0.5 MPa. Then three sets of liquid flow rate ($Q_w$) are adjusted in turn: 266.4 kg·d$^{-1}$, 115.2 kg·d$^{-1}$ and 86.4 kg·d$^{-1}$. The sizes of droplets through atomizing nozzle is measured by Malvern laser grain size analyzer. The test
results and analysis of supersonic atomizing nozzle with a throat diameter of 1.4 mm are illustrated in the followings. Similar analysis can be used for other working conditions and other nozzles.

The gas-liquid ratio is 4898 when adjusting the liquid flow rate \((Q_w)\) to 115.2 kg·d\(^{-1}\). The statistical parameters of droplets (particles) are shown in figures 2 and 3, which are measured by Spraytec. From figure 2, it can be seen that under the given conditions, the volume mean diameter \((d_{43})\) of droplets is 77.45 μm, while the Sauter mean diameter \((d_{32})\) of droplets is 9.55 μm. Overall, the atomization is relatively stable in the test process. Figure 3 shows that droplets with diameter ranging from 10–20 μm account for the largest proportion (peak area). The cumulative fractional curve (red curve) shows that the droplets smaller than 20 μm account for about 65%.

![Figure 2. Statistical analysis of atomized droplet diameter, \(Q_w = 115.2\) kg·d\(^{-1}\).](image)

![Figure 3. Atomized droplet diameter distribution, \(Q_w = 115.2\) kg·d\(^{-1}\).](image)

The gas-liquid ratio is 6531 when adjusting the liquid flow rate \((Q_w)\) to 86.4 kg·d\(^{-1}\). The statistical parameters measured for droplets (particles) are shown in figures 4 and 5. It is illustrated in figure 4 that the volume mean diameter \((d_{43})\) of droplets is 170.20 μm and the Sauter mean diameter \((d_{32})\) is 8.35 μm under the given conditions. The atomization is relatively stable in the test. Figure 5 shows that the droplets with diameters ranging from 0–20 μm account for a large proportion. The cumulative fraction curve (red curve) shows that the droplets with diameters less than 20 μm account for more than 80%. It is obvious that there is a small peak in the range of diameters from 100–500 μm, which indicates that there are very few large droplets after atomization. Due to the existence of large droplets, the measured value of \(d_{43}\) will be much larger.
The droplet is easier to be carried by gas if the diameter is smaller. Comparing figure 3 with figure 5, it is found that the Sauter mean diameter ($d_{32}$) of atomized droplets decreases when the flow rate of gas is fixed and the flow rate of liquid decreases gradually. However, the volume mean diameter ($d_{43}$) increases obviously, which indicates that there are some large droplets after atomization. The number of these large droplets is usually very small (< 10%), but the effect is very significant because these large droplets collide with other droplets to produce more and larger droplets. When the nozzle works at the bottom of the well, it is very likely to cause secondary fluid accumulation after the nozzle, resulting in atomization failure. Therefore, $d_{32}$ and $d_{43}$ should be taken into account comprehensively when choosing nozzle as bottom hole atomizer.

The maximum droplet diameter is about 70 times of the Sauter mean diameter according to the experimental data shown in figures 3 and 5. The maximum droplet diameter is about 0.7 mm, much less than the diameter 8.5 mm which is predicted by Turner theory [12].

4.2. Results and Discussion of Droplet Size

The results of the measurement of droplet diameter are shown in the following figures. The Sauter mean diameter ($d_{32}$) of atomized droplets is plotted and analyzed.

Figure 6 shows the relationship between the Sauter mean diameter ($d_{32}$) and the throat diameter of atomizing nozzle. At the same gas flow velocity, the atomization fineness improves with the increase of gas-liquid ratio. While at a certain gas-liquid ratio, the atomization fineness decreases with the increase of nozzle throat diameter.
When the liquid flow rate is small, the atomization effect of nozzles is very good, and the Sauter mean diameter \(d_{32}\) increases approximately linearly with the increase of nozzle throat diameter, but the change range of the Sauter mean diameter \(d_{32}\) is very small for these atomization nozzles. At medium liquid flow rate, \(d_{32}\) can still maintain an approximate linear growth relationship. At large liquid flow rate, the relationship between \(d_{32}\) and throat diameter is complex. At this time, the atomization effect of nozzles with throat diameters of 1 mm and 1.2 mm becomes very poor. Therefore, in the case of large liquid flow rate, the atomizing nozzle throat diameter has an optimal value.

Figure 7 illustrates the relationship between the Sauter mean diameter \(d_{32}\) and liquid flow rate. If we use \(\Delta d\) to characterize the change for \(d_{32}\) at a certain gas-liquid ratio, the results \(\Delta d_1 = 1.12 \, \mu m\), \(\Delta d_2 = 2.30 \, \mu m\), and \(\Delta d_3 = 14.37 \, \mu m\) can be found in figure 7, indicating that the atomization effect of different atomizing nozzles is small at high gas-liquid ratio. While with the decrease of gas-liquid ratio, the influence of different nozzles on the atomization effect will increase significantly. The results show that the droplet diameter distribution is more and more dispersed with the decrease of gas-liquid ratio at a certain gas flow rate. Generally speaking, when the liquid flow rate is very small, the change range of droplet size with the nozzle throat diameter is small and medium. When the liquid flow rate is large, the droplet size distribution with the nozzle throat diameter is very dispersive.
The experimental results show that the atomizing nozzles used in the experiment can achieve good atomization effect (micron level). When the liquid flow rate is small, the atomizing nozzles have obvious advantages, but when the liquid flow rate is large, the atomization stability of nozzles is poor. In practical application, the more liquid entrainment capacity requires the more cautious the choice of nozzle. At the same velocity, the atomization fineness improves with the increase of gas-liquid ratio.

5. Summary
When the phenomenon of liquid loading occurs in gas wells, it is necessary to remove the liquid accumulation at the bottom of the well by deliquification. In this paper, a method of deliquification with atomizing nozzle is put forward. An experimental bench for atomization of atomizing nozzles is designed and the experimental data are analyzed and summarized.

The atomizing nozzles designed in this paper can achieve good atomization effects. The maximum diameter of atomizing droplets is about 0.7 mm and 70 times of the Sauter mean diameter according to the experimental data, much less than the diameter 8.5 mm which is predicted by Turner theory. The atomizing nozzles have obvious advantages when the gas-liquid ratio is large, but the atomization stability of atomizing nozzles is poor when the gas-liquid ratio is small. The atomization fineness improves with the increase of gas-liquid ratio. The designed nozzles have good atomization performances and show potential application for reducing liquid loading in gas wells.

Acknowledgements
This study is funded by the Key Research and Development Program of Shaanxi Province (NO. 2018GY-074).

References
[1] Li S L 2001 Natural Gas Engineering (Beijing: Petroleum Industry Press) p 314-344.
[2] Lea J F, Nickens H V and Wells M 2011 Gas Well Deliquification (Burlington: Gulf Professional Publishing) pp 6-7.
[3] Wang J Y 2012 Well completion for effective deliquification of natural gas wells Journal of Energy Resources Technology 134 013102.
[4] Ehsan K, Mahdi K and Hassan A 2016 A case study to optimum selection of deliquification method for gas condensate well design: South Pars gas field Ain Shams Engineering Journal 7 847-853.
[5] Guet S and Ooms G 2006 Fluid mechanical aspects of the gas-lift technique Annual Review of Fluid Mechanics 38 225-249.
[6] Lai F P, Li Z P, Wu W C, Yang Z H, Li H and Zhang H 2016 Study on the replacement time of velocity string in production process in tight gas reservoir Journal of Natural Gas Science and Engineering 28 254-261.
[7] Yang J, Jovancicevic V and Ramachandran S 2007 Foam for gas well deliquification Colloids and Surfaces A: Physicochemical and Engineering Aspects 309 177-181.
[8] Yang Z, Luan G H, Liang Z, Deng X and Liao Y H 2009 Research and application on new matching technology of drainage gas production by pumping Natural Gas Industry 29 85-88.
[9] Peng Y, Ye C Q, Sun F J, Wang X Q, Zhu P, Zhu Q, Zhang Y and Wang W L 2018 Drainage gas recovery technology for high-sulfur gas wells by a canned ESP system Natural Gas Industry B 5 452-458.
[10] Wang Y H, Xia H B, Bao K and Qiu W 2019 Research and application of jet pump technology in drainage gas recovery of shale gas at atmospheric pressure Reservoir Evaluation and Development 9 80-84.
[11] Cheng W H, Han Q Q, Li S F, Sun F S and Wang X H 2016 Status of jet pump internal flow numerical simulation study Chemical Engineering Design Communication 42 88-110.
[12] Turner R G, Hubbard M G and Dukler A E 1969 Analysis and prediction of minimum flow rate for the continuous removal of liquids from gas wells Journal of Petroleum Technology 21 1475-82.
[13] Coleman S B, Clay H B, Mccurdy D G and Norris H L 1991 A new look at predicting gas-well load-up Journal of Petroleum Technology 43 329-333.
[14] Nosseir M A, Darwich T A and Sayyouh M H 2000 A new approach for accurate prediction of loading in gas wells under different flowing conditions SPE Production & Facilities 15 241-246.
[15] Li M, Li S L and Sun L T 2001 New view on continuous-removal liquids from gas wells SPE Production & Facilities 17 42-46.
[16] Van’t Westende J M C, Kemp H K, Belt R J, Portela L M, Mudde R F and Oliemans R N A 2006 On the role of droplets in cocurrent annular and churn-annular pipe flow International Journal of Multiphase Flow 33 595-615.
[17] Liu Y H, Luo C C, Zhang L H, Liu Z B, Xie C Y and Wu P B 2018 Experimental and modeling studies on the prediction of liquid loading onset in gas wells Journal of Natural Gas Science and Engineering 57 349-358.
[18] Chang P and Bai B F 2017 An improved method of gas well deliquification using supersonic nozzle International Journal of Heat and Mass Transfer 108 2262-72.
[19] Yang F F and Liu X B 2005 Theoretic analysis and digital simulation of gas in nozzle Refrigeration & Air Conditioning 4 24-26.
[20] Yang C, Chen B, Jiang W L, Gao D R and Jin G J 2016 Analysis and experiment on atomizing characteristics of supersonic nozzle based on Laval effect Transactions of the Chinese Society of Agricultural Engineering 32 5-64.
[21] Calabrese R V, Chang T P K and Dang P T 1986 Drop breakup in turbulent stirred-tank contactors. Part I: Effect of dispersed-phase viscosity AIChE Journal 32 657-666.