Behavior of Friction in Pneumatic Cylinders with Different Relative Humidity

V.-H. Pham^a, T.-D. Nguyen^{a,*}, T.-A. Bui^a

^a Mechanical School, Ha Noi University of Science and Technology, No 1 Dai Co Viet Street, Hai Ba Trung District, Hanoi, 100000, Vietnam.

Keywords:

Friction force
Frictional Behavior
Sliding friction
Pneumatic cylinder
Relative humidity

ABSTRACT

Friction directly affects the motion quality and performance of a pneumatic cylinder system. The frictional behavior of pneumatic cylinder depends on pressure, velocity, diameter, lubrication, and working environment, etc. The relative humidity of the atmospheric environment always affects the friction of dynamic parts. The presence of different humid films on the surface of dynamic parts will cause a change in the frictional behavior of the pneumatic cylinder, which is expressed as the difference between static and dynamic friction. This paper presents the results of research on frictional behavior of a pneumatic cylinder when the atmospheric humidity changes. The studies were conducted at relative humidity of 51 %, 75 % and 99 %, with velocities of 5, 10, 30, 50 and 100 mm/s, respectively. The results show that the effect of atmospheric humidity on the static friction force (F_s), the dynamic friction force (F_D) and the difference between them is clear. The static friction and dynamic friction forces decrease when the humidity increases at the studied velocities. The change in dynamic friction force is 1.5 times greater than static friction. The difference between static and dynamic friction is large at low speeds and low relative humidity, and vice versa. Moreover, it also shows that the stick-slip phenomenon is improved as the relative humidity increases.

* Corresponding author:

Thuy-Duong Nguyen
E-mail: duong.nguyenthuy@hust.edu.vn

Received: 25 April 2020

Revised: 27 May 2020

Accepted: 28 June 2020

© 2020 Published by Faculty of Engineering

1. INTRODUCTION

The reversing linear motion of a pneumatic cylinder is the cause of an unstable friction between seal and piston rod. Therefore, the precise control of position and stability of piston movement during operation is difficult. In order to improve the movement quality of the pneumatic cylinder, it is necessary to find out the rules of frictional behavior of the

pneumatic cylinder. There have been many studies on behavior friction in the pneumatic cylinder. T. Raparelli has shown that with a constant pressure in the cylinder, the relationship between friction force and velocity is an exponential equation and the friction decreases when the piston is lubricated [1]. G. Belforte [2] has proposed a frictional force measuring device of a pneumatic cylinder, in which the movement of piston is controlled by

a hydraulic cylinder under conditions of change in velocity, pressure and cylinder diameter. The results show that the friction depends on the position of the cylinder. For cylinders with the same parameters, the friction force increases as speed and pressure increase. Nouri [3] established an experiment to investigate the friction forces in both preliminary displacement and complete sliding modes of a rodless pneumatic cylinder. The friction in the initial displacement phase mainly depends on displacement, and in the complete sliding phase mainly depends on speed. Chang - Ho investigated the total friction of pneumatic cylinder in two contact states including with and without lubricant at a speed of $5 \div 200$ mm/s. In which, the dynamic friction properties follow the Stribeck curve rule. When lubricated with grease, the friction force is significantly reduced. The research has shown a stick-slip motion phenomenon at low speeds [4]. Xuan Bo Tran and Hideki Yanada proposed a model to survey the dynamic frictional behavior of a pneumatic cylinder in complete sliding mode based on the modified LuGre model, showing a phenomenon of hysteresis at low speeds. At high speeds, friction changes linearly with velocity [5], and the friction in the preliminary displacement phase changes nonlinear with pressures [6]. Wakasawa et al. presented a study on effects of rod and piston packing on frictional behavior in stable and dynamic working conditions. The results showed that the piston packing strongly influenced the behavior of friction in the pneumatic cylinder [7]. In addition, the vibration and friction behavior of pneumatic cylinders are experimentally studied, and the stick-slip motion phenomenon occurs at a speed of 0.010 m/s [8]. These studies mainly focus on the behavior of friction in the pneumatic cylinder with the factors such as p , v , D , vibration, with and without lubrication. The atmospheric environment factor which is characterized by the relative humidity of the air is rarely mentioned in the studies of behavior of friction in pneumatic cylinders.

The relative humidity of the air is one of the important environmental factors that directly influence the friction and wear of the material pairs. The relative humidity interacts with the surfaces of sliding material pairs and changes its contact properties. Depending on the relative humidity of the air, the behavior of friction and

wear of material pairs will have significant changes. The frictional behavior of material pairs moving relative to each other increases as the relative humidity decreases that are shown in the published documents [9-15].

Vietnam has a humid tropical monsoon climate, the relative humidity (RH) varies seasonally from 51 % (in summer) to ~ 99 % (in spring), which will affect the abrasion behavior of friction of pairs of materials when working. Nguyen Anh Tuan et al. has studied the effect of Vietnam climate (with relative humidity changing from 60 % to 100 %) on wear of iron and steel materials. The results show that the wear increases rapidly when the relative humidity increases [16]. The pneumatic cylinders working in the climatic environment of Vietnam, the behavior of friction will be changed, resulting in a difficulty to precisely control the position and stabilize the speed of pneumatic cylinders.

This paper presents research on frictional behavior of a pneumatic cylinder when humidity changes with the climate characteristics of Vietnam. The relationship between the difference of static and dynamic friction with air humidity is also discussed below.

2. EXPERIMENTAL APPARATUS AND METHOD

The experimental apparatus is shown in Fig. 1. It consists of a pneumatic cylinder and a servo motor system. The piston is fixed while the cylinder can move relative to the piston. The motion of cylinder is driven with velocities precisely controlled by a servo-driven motor. The equipment system is located in the BKNA1 humidity chamber, the servo motor and the measuring system are located outside the humidity chamber with a humidity can be changed in a range of $51 \div 99$ % ± 2 %. Displacement of the cylinder is measured by a displacement transducer DTH-A with an accuracy less than 0.1 % RO. The friction force of the pneumatic cylinder is measured by a loadcell with a rated output of 50 N and an accuracy less than 0.02 % FS, which is set between the piston rod via a spherical joint and a fixed plate. The principle diagram for measuring friction force of the pneumatic cylinder is shown in Fig. 2.

Fig. 1. A schematic view of the experimental apparatus: 1-Humidity chamber, 2 - Pneumatic cylinder, 3-Piston rod, 4 - Spherical joint, 5- Load cell, 6 - Data system, 7 - Displacement transducer, 8 - Ball screw, 9 - Coupling.

Fig. 2. A diagram for measuring friction force.

Force equilibrium equation of a piston is given by a formula as follows:

$$\vec{F}_1 + \vec{F}_2 + \vec{F}_3 = 0 \quad (1)$$

In which:

$\vec{F}_1$: Friction force between piston seal and cylinder;

$\vec{F}_2$: Friction force between seal and piston rod;

$\vec{F}_3$: Balancing force of load cell.

The displacement and the friction force are conducted, processed, and displayed on the computer screen through the software DasyLab 11.0. The screen interface shows the results of

measuring friction characteristics including the static friction force F_S and dynamic friction force F_D according to displacement stroke. The detail experimental conditions are shown in Table 1.

Table 1. Experimental Conditions.

No	Parameters	Experimental conditions
1	Pneumatic cylinder TGC50x150 - S; STNC	Diameter (D): 50 mm, Rod diameter (d): 20 mm, Stroke (h): 150 mm
2	Velocity (v)	5, 10, 30, 50, 100 mm/s
3	Relative Humidity (RH)	51 %, 75 %, 99 %
4	Surface conditions	No lubrication with humid environments
5	Pressure (p)	Atmosphere

3. RESULT AND DISCUSSION

3.1 Behavior of friction in pneumatic cylinder with different humidity

The experiment was conducted in a sequence: Adjust the relative humidity of 51 %. Estimate

the behavior of friction characteristics at speeds of 5 mm/s, 10 mm/s, 30 mm/s, 50 mm/s, and 100 mm/s, respectively. Each test was repeated three times to ensure the reliability of the experiment results. Similarly, the other experiments were carried out at humidity of 75 % and 99 %. Figure 3 shows the frictional behavior in the pneumatic cylinder at humidity values of 51, 75, 99 % with $v = 5$ mm/s.

As shown in Figure 3, when the relative humidity changes, the frictional behavior in the pneumatic cylinder is a difference, it is indicated by the static and dynamic friction values at the same relative humidity. At $v = 5$ mm/s and the humidity increase from 51 % to 99 %, the friction force (F_s , F_d) is reduced, the static friction force decreases by 6.54 N, the dynamic friction force decreases by 2.82 N. On the other hand, the difference of static and dynamic friction forces $\Delta = F_s - F_d$ decreases about ~19 % when the humidity increases from 51 % to 99 %. Thus, the phenomenon of stick-slip of the pneumatic piston cylinder at low speeds can be improved when the humidity increases from 51 to 99 %.

Fig. 3. Behavior of friction in a pneumatic cylinder at humidity of 51 %, 75 %, 99 % and $v = 5$ mm/s.

Table 2. Experimental data.

v	$RH = 51\%$		$RH = 75\%$		$RH = 99\%$	
(mm/s)	$F_s(N)$	$F_d(N)$	$F_s(N)$	$F_d(N)$	$F_s(N)$	$F_d(N)$
5	40.45	20.1	37.89	19.13	33.91	17.28
10	28.2	16.94	26.4	15.7	23.43	13.52
30	15.61	12.9	14.8	11.84	13.27	9.93
50	17.57	14.89	16.66	13.76	15.38	11.88
100	22.52	20.9	21.68	19.85	20.23	17.8

Similarly, the experiments at speeds of 10, 30, 50 and 100 mm/s were conducted, the results are shown in Table 2.

3.2 Effect of relative humidity on static and dynamic friction forces

Static friction force

The behavior of static friction (F_s) in a pneumatic cylinder with humidity of 51 %, 75 %, and 99 % at the studied speeds is shown in Fig. 4.

Fig. 4. Behavior of static friction F_s with different humidity and speeds.

The behavior of static friction force is in the form of Stribeck curve. The highest static friction force at $v = 5$ mm/s and $RH = 51\%$. Thus, at low speeds and the low RH values, the static friction force is larger, which can be explained that a lubricating moisture film is difficult to form on the surface of the piston rod. When the humidity increases from 51 % to 99 % at different speeds, the static friction force decreases by 10÷16 % due to the appearance of moisture film on the piston rod surface. Reducing static friction force can reduce the delay time of initial movement of the pneumatic cylinder.

Dynamic friction force

The behavior of dynamic friction (F_d) in pneumatic cylinder with the humidity of 51 %, 75 % and 99 % at the studied speeds is shown in Fig. 5.

Figure 5 shows that the dynamic frictional behavior of the pneumatic cylinder at the relative humidity of 51, 75, 99 %, completely follows the Stribeck curve when the speed increases from 5 mm/s to 100 mm/s. The dynamic friction force reaches a minimum value with the moving speed of 30 mm/s. When the humidity increases from 51 % to 99 % at all speeds, the dynamic friction reduces by 14÷24 %. Thus, in the surveyed speed range, the effect of relative humidity on dynamic friction is 1.5 times greater than that of the static

friction force, due to the lubrication effect of a moisture film.

Fig. 5. Behavior of dynamic friction F_D with different humidity and speeds.

On the other hand, when the relative humidity varies from 51 % to 99 %, the effect of the relative humidity changing from 51 % to 75 %, on the behavior of friction is lower than that of the relative humidity changing from 75 % to 99 %. This can be explained by the condensation of a moisture film on the piston rod surface. With a higher humidity, it will be easy to create a moisture film on the piston rod surface due to the condensation of steam near saturation. It plays a role of the lubricant film when the movement speed changes.

3.3 Simultaneous behavior of static and dynamic friction with different humidity

At the humidity of 51 %, the experiment results show that the friction force (F_s , F_D) decreases rapidly when the speed increases from 5 mm/s to 30 mm/s and after that the friction force increases slowly when the speed increases from 30 mm/s to 100 mm/s. Thus, there exists a minimum region as shown in Fig. 6.

Fig. 6. Behavior of static and dynamic friction at RH of 51% and different speeds.

The difference of static and dynamic friction forces ΔF ($\Delta F = F_s - F_D$) decreases from 20.35 N to 1.62 N when the movement speed increases from 5 to 100 mm/s. When the speed increases from 5 to 30 mm/s, the difference ΔF rapidly decreases from 20.35 N to 2.72 N. With the speed increases from 30 to 100 mm/s, the difference of ΔF slowly decreases from 2.72 to 1.62 N. Thus, moving at low speed, a large ΔF difference can be a main cause of stick – slip phenomenon.

Similarly, the studies with RH of 75 % and 99 % shown the simultaneous behavior of static, dynamic friction and its difference ΔF when the speed increased from 5 to 100 mm/s is shown in Figs. 7 and 8. At the relative humidity of 75 %, the difference ΔF decreases from 18.76 N to 2.96 N with the speed changing from 5 to 30 mm/s and slightly decreases from 2.96 N to 1.83 N when the speed increasing from 30 to 100 mm/s, as shown in Fig. 7.

Fig. 7. Behavior of static and dynamic friction at RH of 75 % and different speeds.

Fig. 8. Behavior of static and dynamic friction at RH of 99 % and different speeds.

At the relative humidity of 99 %, the result is shown in Fig. 8. It can be seen that, the difference ΔF decreases from 16.63 N to 3.34 N in the speed range of 5 to 30 mm/s and slightly

decreases from 3.34 to 2.43 N when the speeds increasing from 30 mm/s to 100 mm/s.

The influence of relative humidity (51, 75, 99 %) and the movement speeds (5, 10, 30, 50, 100 mm/s) on the behavior of ΔF in the pneumatic cylinder is shown in Fig. 9.

Fig. 9. Behavior of ΔF with different RH and speeds.

In which, with low speed changing from 5 to 10 mm/s, the value of ΔF at RH = 51 % is 20 % greater than that at RH = 99 %, this could be the cause of stick-slip friction. Due to its low speeds and low humidity, the moist film lubrication effect does not appear.

In the higher speed range of 30 to 100 mm/s, the value of ΔF at RH = 99 % is greater than that at RH = 51 %. This shows that at a high humidity, the piston rod surface has a good lubrication condition which reduces the dynamic friction force, resulting in an increase in the ΔF value.

At the velocity approximately 16 mm/s, the effect of relative humidity is negligible, ending the region with risk of stick-slip and moving to the complete sliding zone.

4. CONCLUSION

Frictional behavior of a pneumatic piston-cylinder with different humidity has been studied. The behavior of friction on pneumatic cylinders were determined by using an experimental equipment system. The research results show that the frictional behavior of the pneumatic cylinder depends on the relative humidity of the air and the speeds of displacement. Besides, it also shows that the force variation ΔF depends on the atmospheric humidity and the speed of movement, which are summarized in the points below:

1. The static and dynamic friction forces of the pneumatic cylinder decrease when the relative humidity increases from 51 % to 99 %, in all surveyed speeds.
2. The effect of relative humidity on dynamic friction force is 1.5 times greater than static friction. The static friction force tends to decrease from 10 ÷ 16 %, while the dynamic friction force tends to decrease 14 ÷ 24 % when relative humidity increases from 51 to 99 % at all surveyed speeds. This affects the dynamics of the automatic system when driven by a pneumatic cylinder.
3. The difference of static and dynamic friction forces ΔF at the relative humidity of 51 % is higher than that at the relative humidity of 99 % with the speed changing from 5 to 10 mm/s and vice versa when the speed changing from 30 to 100 mm/s.
4. The great difference between static and dynamic friction forces ΔF with the speed from 5 to 10 mm/s may cause the stick-slip motion phenomenon. At high relative humidity, the stick-slip motion phenomenon is smaller than that at low relative humidity.
5. This study does not mention the working pressure of pneumatic cylinder to confirm the obvious effect of humidity on the friction. The behavior of friction in the pneumatic cylinder with different conditions of humidity, speed and working pressure is undergoing for further study.

REFERENCES

- [1] T. Raparelli, A.M. Bertettot, L. Mazzat, *Experimental and numerical study of friction in an elastomeric seal for pneumatic cylinders*, Tribology International, vol. 30, iss. 7, pp. 547-552, 1997, doi: [10.1016/S0301-679X\(97\)00015-7](https://doi.org/10.1016/S0301-679X(97)00015-7)
- [2] G. Belforte, G. Mattiazzo, S. Mauro, L.R. Tokashiki, *Measurement of Friction Force in Pneumatic Cylinders*, Tribotest, vol. 10, iss. 1, pp. 33-48, 2006, doi: [10.1002/tt.3020100104](https://doi.org/10.1002/tt.3020100104)
- [3] B.M.Y. Nouri, *Friction Identification in Mechatronic Systems*, ISA Transactions, vol. 43, iss. 2, pp. 205-216, 2004, doi: [10.1016/S0019-0578\(07\)60031-7](https://doi.org/10.1016/S0019-0578(07)60031-7)
- [4] H. Chang, C.-W. Lan, C.-H. Chen, T.-T. Tsung, J.-B. Guo, *Measurement of frictional force characteristics*

- of pneumatic cylinders under dry and lubricated conditions, *Przegląd Elektrotechniczny* (Electrical Review), vol. 88, no. 7b, pp. 261-264, 2008.
- [5] X.B. Tran, H. Yanada, *Dynamic Friction Behaviors of Pneumatic Cylinders*. *Intelligent Control and Automation*, vol. 4, no. 2, pp. 180-190, 2013, doi: [10.4236/ica.2013.42022](https://doi.org/10.4236/ica.2013.42022)
- [6] T.X. Bo, D.V. Long, H. Yanada, *Dynamic friction behavior in pre-sliding regime of pneumatic actuators*, *ASEAN Engineering Journal*, vol. 7, no 1, pp. 50-68, 2017.
- [7] Y. Wakasawa, Yuta Kohashi, Naoto Ayada, Hideki Yanada, *Friction Characteristics of Pneumatic Cylinder*, in *The 4th International Conference on Design Engineering and Science, ICDES 2017 Aachen, Germany, September 17-19, 2017*.
- [8] Y. Wakasawa, Y. Ito, H. Yanada, *Friction and Vibration Characteristics of Pneumatic Cylinder*, in *The 3rd International Conference on Design Engineering and Science, ICDES 2014 Pilsen, Czech Republic, August 31 – September 3, 2014*.
- [9] M.A. Chowdhury, M.M. Helali, *The Effect of Frequency of Vibration and Humidity on the Coefficient of Friction*, *Tribology International*, vol. 39, iss. 9, pp. 958-962, 2006, doi: [10.1016/j.triboint.2005.10.002](https://doi.org/10.1016/j.triboint.2005.10.002)
- [10] Y. Imada, K. Nakajima, *Effect of humidity on the friction and wear properties of Sn*, *Journal of Tribology*, vol. 117, iss. 4, pp. 737-741, doi: [10.1115/1.2831545](https://doi.org/10.1115/1.2831545)
- [11] Y. Imada, *Effect of humidity and oxide products on the friction and wear properties of mild steel*, *Japanes Journal of Tribology*, vol. 114, pp. 131-40, 1996.
- [12] J.K. Lancaster, *A review of the influence of environmental humidity and water on friction, lubrication and wear*, *Tribology International* vol. 23, iss. 6, pp. 371-389, 1990, doi: [10.1016/0301-679X\(90\)90053-R](https://doi.org/10.1016/0301-679X(90)90053-R)
- [13] M.A. Chowdhury, M. Helali, *The Effect of Relative Humidity and Roughness on the Friction Coefficient under Horizontal Vibration*, *The Open Mechanical Engineering Journal*, vol. 2, pp. 128-135, 2008, doi: [10.2174/1874155X00802010128](https://doi.org/10.2174/1874155X00802010128)
- [14] M.A. Chowdhury, *Effect of Sliding Velocity and Relative Humidity on Friction Coefficient of Brass Sliding against Different Steel Counterfaces*, *International Journal of Engineering Research and Applications (IJERA)*, vol. 2, iss. 2, pp. 1425-1431, 2012.
- [15] M.A. Chowdhury, M.M. Helali, *The effect of frequency of vibration and humidity on the wear rate*, *Wear*, vol. 262, iss. 1-2, pp. 198-203, 2007, doi: [10.1016/j.wear.2006.05.007](https://doi.org/10.1016/j.wear.2006.05.007)
- [16] N.A. Tuan, N.Y. Doan, P.V. Hung, N.N. Thai, *Wear of material in humid – tropical conditions*, *Wear*, vol. 162-164, pp. 1066-1067, 1993, doi: [10.1016/0043-1648\(93\)90124-5](https://doi.org/10.1016/0043-1648(93)90124-5)