Influence of Humid Air Temperature on Friction Behavior in Pneumatic Cylinder

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

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

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ABSTRACT

In the air, water vapor always exists and impacts directly on the friction surface between the piston rod and the rod seal. Water vapor in the air forms moisture film on the surface of the piston rod. In some cases, it plays a role as a lubricant. In general, to evaluate the amount of water vapor in the air, we use two measuring quantities that are relative humidity and absolute humidity. Although the relative humidity is equal at different temperatures, the amount of water vapor in the air is not the same and can be determined by absolute humidity. The paper presents the results of research on the effect of humid air temperature on the frictional behavior of the piston rod and a rod seal, under constant relative humidity conditions. The studies were conducted at a temperature of 15°C, 32°C, and 49°C, with velocities of 5, 10, 30, 50, and 100 mm/s, respectively. The results show that the friction between the piston rod and rod seal (including a maximum force of static friction - F_s and dynamic friction- F_D) changes according to the ambient temperature of the humid air. When the temperature increases from 15°C to 49°C, the friction force decreases approximately 10 - 18%. The change in maximum force static friction is 1.2 times greater than dynamic friction force.

* Corresponding author:

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

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1. INTRODUCTION

Water vapor always exists in the air. Based on the amount of water vapor, we can distinguish dry air and humid air. On the other hand, the air temperature is the evidence to classify temperate, subtropical, or tropical climate, etc. In the environment, humidity and air temperature are always related and affect each other. The moisture film on the surface of the friction pair is formed through the

condensation of water vapor in the air at the survey temperature. Compared with dry friction, the moisture film on the friction surface is considered as a lubricant. Relative humidity and absolute humidity are two measuring quantities usually used to assess the amount of water vapor in the humid air. Relative humidity RH% is the ratio between the amount of current water vapor in the air and the amount of saturated water vapor at a given temperature. Absolute humidity is the

total mass of water vapor present in a volume of air at a given temperature. The hotter the air is, the more water it can contain. Therefore, with the same relative humidity at several temperatures, the amount of water vapor is different and is shown in absolute humidity. The humid air affects the frictional properties of interaction surfaces directly, so there have been lots of studies about the effect of relative humidity (RH) on the friction of various pairs of material. The result has shown that the friction force decreased as the increased relative humidity of the humid air [1-7].

The motion of the pneumatic cylinder is straight influenced by the friction between the piston rod and rod seal. But the frictional behavior of this friction depends on velocity, pressure, lubricant, diameter as well as the humid air's humidity and temperature. Friction can cause power reduction, stick-slip motion, and making difficulties in controlling the systems. So, a thorough understanding of the pneumatic cylinder's frictional behavior under various temperature values of the humid air is essential in their design and control. The studies in this field are very diverse and complex. They are often demonstrated through experiments.

The friction behavior of a pneumatic cylinder working in a humid environment has been mentioned in a lot of studies. The study carried out by Niko Heraković [8] has shown that pressure and temperature significantly affect the friction force in a pneumatic cylinder. In the temperature range from 20°C to 22°C, the friction force decreases on average from 2 to 2.5N when increasing by 1°C. T. Raparelli [9] has combined practical and numerical-stimulating studies on the friction of a pneumatic cylinder under variable pressure and velocity conditions, with and without lubrication. The results show the similarity between experimental and numerical simulation. The friction force grows following velocity and pressure and decreases in the lubricated condition. Another study of friction pneumatic seal by Abdelhak AZZI [10] shows the effect of pneumatic pressure on the friction is greater than that of the velocity. The seal geometry has a significant effect on the friction, which is magnified quickly as the seal diameter increase. As the temperature and

velocity increase, the study of Takahiro Kosaki, Manabu Sano [11] found that the friction force in the pneumatic cylinder declines and tends to depend more on the high velocity. Nouri [12] investigated the friction force of a non-rod pneumatic cylinder in two states (a preliminary displacement and a complete sliding). The results show that the friction force depends on transposition in the preliminary displacement and depends on the velocity in the completely sliding stage. The study of Chang - Ho [13] has indicated that the dynamic friction properties of a pneumatic cylinder follow the Stribeck curve. The friction force was decreased in the lubricated condition, and the stick-slip occurred at a low velocity. Xuan Bo Tran and Hideki Yanada [14] gave a model to investigate the dynamic-frictional behavior of the pneumatic cylinder in a completely sliding state based on the modified LuGre model, which showed that there is a hysteresis phenomenon at low speed. At high speed, friction is linearly dependent on velocity. In the initial displacement stage, the friction force in the pneumatic cylinder changes nonlinearly with pressure as a result of [15]. Besides, the stick-slip friction phenomenon in the pneumatic cylinder occurring at low speeds has been confirmed in experimental studies at the velocity of 0,010 m/s [16]. Pham Van Hung et al [17,18] studied the impact of the relative humidity in the working area on the frictional behavior of the pneumatic cylinder. The results indicated that the friction force decreases while the humidity rose from 51 to 99%. The dynamic friction force changed 1.5 times more than the maximum force of static friction.

The above-presented studies mainly focus on the frictional behavior in the pneumatic cylinder with external influencing factors such as pressure, velocity, with and without lubrication. Particularly, there are a few reports that have mentioned the effect of humidity and temperature of the humid air but only at a low temperature with a little modification - it is the temperate climate's characteristic. Tropical monsoon climate has high relative humidity and has a large change of thermal amplitude that affect the friction of the pneumatic cylinder. The issue has not been studied much. There are some researches done

by Nguyen Anh Tuan, Pham Van Hung [19] show the Vietnam humid tropical climate effect on the wear characteristics of cast iron. Experiments were conducted at several temperatures of 16°C, 33°C, and 50°C; relative humidity values of 51%, 75%, and 99%. The results showed that the wear of cast iron changes according to the given relative humidity and air temperature. The wear appeared less at low humidity and high temperature. By contrast, it occurred much at high humidity and high temperature.

During the operation, the friction between the piston rod and rod seal is directly impacted by the humid air. The change of the temperature and the humidity will lead to the variation of the frictional behavior in the pneumatic cylinder that puts difficulty in controlling the stopping position precisely and stabilizing velocity.

This paper presents the results of practical research on the frictional behavior of the pneumatic cylinder when the humid air temperature changes according to the characteristics of the Vietnamese climate. It is the dependence of the friction force (piston rod and rod seal) in the pneumatic cylinder on the variation of the humid air temperature when the relative humidity is kept unchanged.

2. METHOD AND EXPERIMENTAL APPARATUS

2.1 Method of measuring friction force in a pneumatic cylinder

The friction forces in a pneumatic cylinder include: Sliding friction force F_1 of the piston seal - cylinder and F_2 of the piston rod and rod seal, as shown in figure 1. The force equilibrium F_3 equation of a piston is given by a formula as follows:

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

Fig.1. A diagram for measuring friction force [18]

where:

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

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

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

The friction force in the pneumatic cylinder is obtained from the loadcell sensor when the cylinder has a relative translational motion to the piston. Select the position and the stroke of the pneumatic cylinder properly to prevent the impact of the cushioning seal in the damping region to the survey results. The method can precisely measure the friction force in the pneumatic cylinder by the load cell. In the experiment, the friction condition between the piston seal and the cylinder was kept stable. The change of humid air temperature will affect immediately on the piston rod and rod seal.

2.2 Experimental equipment

The experimental apparatus is shown in Fig. 2.

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

In this set-up test, a pneumatic cylinder with its piston diameter, piston rod diameter, and a stroke of 50 mm, 20 mm, and 150 mm, respectively, was used. The piston is fixed and the cylinder moves in relative motion relative to the piston. The cylinder movement is performed by a servo-electric motor and driven by a ball screw. It was measured by a DTH-A

displacement transducer with an accuracy of $\pm 0.1\%$ RO. The friction force acting on the piston is determined by a load cell S-type LOADCELL GSL - 301A, 5kG with an accuracy of 0.02% FS. A one-end of a load cell is fixed to the machine stand while the other one is connected to the piston rod through a spherical joint to ensure measurement results are correct. The whole of the mechanical-driven system and the pneumatic cylinder are put in an environmental chamber. The servo-electric motor and the measuring system are located completely outside the thermostat cabinet to avoid all the effects of the environment inside it. The environmental chamber is capable of meeting the variation of temperature from 15 to $50^\circ\text{C} \pm 1^\circ\text{C}$, and RH from 50 to $99\% \pm 2\%$. The data obtained from the straight gauge and the load cell are converted to digital signals via an ADC converter. After that, they are processed and displayed on the computer screen by DasyLab 11.0 software.

The screen interface shows the results of measuring friction characteristics that include both the maximum force of static friction (F_s) and dynamic friction force (F_D) according to displacement stroke. The detailed experimental conditions are presented in Table 1.

Table 1. Experimental conditions

Parameters	Experimental conditions
Pneumatic cylinder	TGC50x150 – S; STNC
Velocity (v)	5, 10, 30, 50, 100 mm/s
Relative Humidity (RH)	75%
Temperature (T)	15, 32, 49°C
Surface conditions	No lubrication, with humid environments
Pressure (P)	Atmosphere

3. RESULTS AND DISCUSSION

3.1 Friction behavior of pneumatic cylinders

The experiment was conducted in a sequence: Set the relative humidity of the environment chamber to be constant at $RH = 75\%$. Then, set the temperature at 15°C , examine the frictional properties at the speeds of 5 mm/s, 10 mm/s, 30 mm/s, 50 mm/s, 100 mm/s in order. At each velocity, the static and dynamic friction values are determined and displayed on the screen

then stored. The friction characteristics of the pneumatic cylinder at temperature $T = 15^\circ\text{C}$ and $v = 5\text{ mm/s}$ are shown in Fig.3.

Fig 3. Friction behavior of pneumatic cylinder, $v = 5\text{ mm/s}$

Friction force as a function of displacement [20], including Stage I - preliminary displacement; Stage II - breakaway, and Stage III - sliding. After the preliminary displacement stage, there is a sudden decrease from the maximum force of static friction (F_s) to dynamic friction force (F_D). In this case, the difference between F_s and F_D is quite extensive: $F_s = 2F_D$. This may be the cause of the friction phenomenon Stick-slip.

Similar experiments at other velocity and temperature values were conducted, each test carried out 03 parallel experiments, and the results are shown in Table 2.

Table 2. Experimental Data

v (mm/s)	$T = 15^\circ\text{C}$		$T = 32^\circ\text{C}$		$T = 49^\circ\text{C}$	
	F_s (N)	F_D (N)	F_s (N)	F_D (N)	F_s (N)	F_D (N)
5	40.51	20.39	37.89	19.01	35.87	18.37
10	29.02	16.68	26.4	15.7	24.87	14.98
30	16.85	12.9	14.8	11.84	13.85	10.98
50	18.56	15.12	16.66	13.76	15.75	12.71
100	23.7	21.18	21.68	19.85	20.75	18.73

3.2 Influence of humid air temperature on friction force of pneumatic cylinders

The changes in the values of the F_s and F_D at different velocities of the pneumatic cylinder when the temperature of the humid air increased from 15°C to 49°C are shown in Figure 4 (a, b).

Fig 4. The graph of the dependence of (F_s , F_D) on T at different velocities

As shown in Figure 4, it can be seen that at a velocity of 5 mm/s, the F_s decreased from 40,51 N to 35,87 N, and the F_D decreased from 20,39 N to 18,37 N when the temperature increased by 15 $^{\circ}\text{C} \div 49^{\circ}\text{C}$. Similarly, at the velocities of 10, 30, 50, and 100 mm/s, respectively, and they also show that the F_s and F_D decreased when the temperature of the humid air increased by 15 $^{\circ}\text{C} \div 49^{\circ}\text{C}$. Besides, the result shows that the F_s decreased by 12 $\div$ 18% and that the F_D decreased by 10 $\div$ 15% when the temperature increased by 15 $^{\circ}\text{C} \div 49^{\circ}\text{C}$ at all the given velocities. Thus, the influence of the temperature of the humid air on the F_s was 1.2 times greater than that on the F_D . The high maximum force of static friction made the pneumatic system spend more time on the preliminary displacement of the piston.

The variation of friction force in a pneumatic cylinder while the velocity changes from 5 mm/s, 10mm/s, 30 mm/s, 50 mm/s, to 100 mm/s in several conditions of a humid air temperature of 15 $^{\circ}\text{C}$, 32 $^{\circ}\text{C}$, 49 $^{\circ}\text{C}$ is showed in figure 5.

Fig 5. Friction force (F_s , F_D) dependence on the velocity (v) at different temperature

Figure 5 shows the relation between frictional behavior (F_s , F_D) in a pneumatic cylinder and velocity at several temperatures of 15 $^{\circ}\text{C}$, 32 $^{\circ}\text{C}$, and 49 $^{\circ}\text{C}$, which has a form of a Stribeck curve. As the temperature increases from 15 $^{\circ}\text{C}$ to 32 $^{\circ}\text{C}$, the friction force decreases more strongly compared with from 32 $^{\circ}\text{C}$ to 49 $^{\circ}\text{C}$. Thus, at a low temperature of humid air, the friction force is larger than that at a high temperature, which is also consistent with published studies on the individual effect of temperature. It can also be explained that at a high temperature, the rod seal in a pneumatic cylinder

is more flexible that leads to the increasing of its elasticity. On the other hand, at a low temperature, the absolute amount of water vapor in humid air is less than at a high temperature compared with the same relative humidity condition of 75%. Therefore, the lubricating function of the moisture film at a high temperature is more effective. To put it simply, when the temperature of the humid air is high, the lubricating effect of the moisture film on the piston rod's surface is better, reducing the friction in the movement of a pneumatic cylinder.

The difference between the maximum force of static friction and dynamic friction ($\Delta F = F_s - F_d$) is shown in Fig 6. At the same speed, the value of ΔF at $T = 15^\circ\text{C}$ is $115 \div 120 \%$ than at $T = 49^\circ\text{C}$. In lower speed $5 \div 10 \text{ mm/s}$, ΔF greater $3 \div 10$ times than speed $50 \div 100 \text{ mm/s}$. Thus, in low speed, the stick-slip phenomenon was easily leading to instability during the start and stop phase, and affect the positioning accuracy of the pneumatic cylinder. Due to the low speed and low temperature, the formation of a wet film on the piston rod is small and insufficient to give a lubricating effect.

Fig 6. The behavior of $\Delta F = F_s - F_d$ depended on T and v

In the higher speed range of 50 to 100 mm/s, the value of ΔF is significantly reduced. This shows that the piston rod surface has a lubrication humid film which reduces the maximum force of static friction, resulting in a reduction in the ΔF value. The reduction of ΔF can make the stability of the positioning of the pneumatic cylinder.

Through the above results of researching and analyzing, the maximum force of static friction F_s depends on the temperature of humid air and the velocity in pneumatic cylinders that is shown in Figure 6, and it can be described by the following mathematical functions (2) with $R^2 > 0.95$ when $\text{RH} = 75\%$.

$$F_s(T, v) = 9.998 + 0.2875 \cdot v - 0.2214 \cdot T - 0.0013 \cdot v^2 + 0.0016 \cdot T^2 + 0.0005 \cdot v \cdot T - 0.522 \cdot e^{(-3.591 \cdot v)} + 53.06 \cdot e^{(-0.1024 \cdot v)} \quad (2)$$

Fig 7. The maximum force of static friction (F_s) depends on the temperature of humidity air (T) and velocity (v)

Similar to dynamical friction force F_d , have got mathematical functions (3) with $R^2 > 0.95$ when $\text{RH} = 75\%$ and described by Figure 7:

$$F_d(T, v) = 2.583 + 0.3158 \cdot v - 0.089 \cdot T - 0.0011 \cdot v^2 - 0.0006 \cdot T^2 + 0.0002 \cdot v \cdot T + 23.23 \cdot e^{(-0.067 \cdot v)} \quad (3)$$

Fig 8. Dynamical friction force (F_d) depends on the temperature of humidity air (T) and velocity (v)

The equations (2) and (3) and Figure 7 and Figure 8 show the simultaneous influence of the temperature of humid air and the velocity on the F_s and F_d in the pneumatic cylinder, but it's very different about level. In particular, the effect of velocity on the friction force is an exponential form, while the effect of temperature of the humid air is a linear approximation.

The friction equation depending on the temperature of humid air together with the velocity can be applied to precisely control the position of pneumatic cylinder systems such as the automatic change tool on CNC machine, which uses pneumatic cylinders as a driving force. Thus, it is possible to accurately determine the stop position under different conditions of humid air and velocity.

4. CONCLUSION

The effect of the temperature of humid air and velocity on the friction characteristics of a pneumatic cylinder was studied. The static and dynamic friction forces were measured using an experimental equipment system, which is summarized in the points below:

1. It was found that the maximum force of static friction and dynamic friction forces of the pneumatic cylinder decrease when the temperature of humid air increased in all surveyed velocities.
2. The effect of the temperature of humid air on the maximum force of static friction F_s is 1.2 times greater than that on dynamic friction F_d . The F_s tends to decrease from 12 ÷ 18%, while the dynamic friction force tends to decrease 10 ÷ 15% when the temperature increased by 15°C ÷ 49°C at all surveyed speeds. So that, $\Delta F = F_s - F_d$ depends on T, v and effect to the stability of the positioning of the pneumatic cylinder.
3. The experimental equations force $F_s(T, v)$ and $F_d(T, v)$ can be represented by the dynamic equations of the motion of pneumatic cylinders while changing the temperature of humid air values. It will improve the position accuracy and stabilize the velocity of a pneumatic cylinder.
4. In the process of studying the effects of the humid air on the movement of a pneumatic cylinder, it is necessary to pay attention to both environmental factors that are temperature and humidity. They have a direct impact on the dynamics of the automatic system when driven by a pneumatic cylinder.

REFERENCES

- [1] M.A. Chowdhury, 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)
- [2] Y. Imada, K. Nakajima, *Effect of humidity on the friction and wear properties of Sn*, Journal of Tribology, vol. 117, iss. 4, pp. 737-44, 1995, doi: [10.1115/1.2831545](https://doi.org/10.1115/1.2831545)
- [3] I. Yasuo, *Effect of humidity and oxide products on the friction and wear properties of mild steel*, Journal of Japanese Society of Tribologists, vol. 41, iss. 10, pp. 844-851, 1996.
- [4] 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)
- [5] 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, 128-135, 2008, doi: [10.2174/1874155X00802010128](https://doi.org/10.2174/1874155X00802010128)
- [6] M.A. Chowdhury, D.M. Nuruzzaman, M.A. Hannan, *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.
- [7] 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)
- [8] N. Herakovič, J. Duhovnik, D. Noe, *Friction Force in the Pneumatic Cylinder*, Strojniški vestnik - Journal of Mechanical Engineering, vol. 38, iss. 10-12, pp. 279-288, 1992.
- [9] T. Raparelli, A.M. Bertetot, 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)
- [10] A. Azzi, A. Maoui, A. Fatu, S. Fily, D. Souchet, *Experimental study of friction in pneumatic seals*, Tribology International, vol. 135, pp. 432-443, 2019, doi: [10.1016/j.triboint.2019.03.018](https://doi.org/10.1016/j.triboint.2019.03.018)
- [11] T. Kosaki, M. Sano, *Effect of Sliding Surface Temperature on Frictional Force in a Pneumatic Cylinder*, Transactions of the Japan Hydraulics & Pneumatics Society, vol. 32, iss. 4, pp. 98-103, 2001, doi: [10.14888/jfps1998.32.98](https://doi.org/10.14888/jfps1998.32.98)

- [12] 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)
- [13] 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, vol. 88, no. 7b, pp. 261-264, 2008.
- [14] 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)
- [15] 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.
- [16] Y. Wakasawa, Y. Ito, H. Yanada, *Friction and Vibration Characteristics of Pneumatic Cylinder*, in 3rd International Conference on Design Engineering and Science, 31 August - 3 September, 2014, ICDES 2014 Pilsen, Czech Republic, pp. 155-159.
- [17] T.-D. Nguyen, V.-H. Pham, *Study of the effects of relative humidity and velocity on the friction characteristics of pneumatic cylinders*, International Journal of Modern Physics B, vol. 34, no. 22-24, pp. 2040139-159, 2020, doi: [10.1142/S0217979220401396](https://doi.org/10.1142/S0217979220401396)
- [18] V.-H. Pham, T.-D. Nguyen, T.-A. Bui, *Behavior of Friction in Pneumatic Cylinders with Different Relative Humidity*, Tribology in Industry, vol. 42, no. 3, pp. 400-406, 2020, doi: [10.24874/ti.878.04.20.07](https://doi.org/10.24874/ti.878.04.20.07)
- [19] N.A. Tuan, N. Doan Y, 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)
- [20] I.V. Kragelsky, *Friction Wear Lubrication: Tribology Handbook*, Pergamon Press, 1981.