



On the Fire Hose Kickback Force in Solid Water Streams

Dac Nguyen *, Fire Service Institute, University of Illinois, Urbana, IL, USA

Richard M. Kesler, Fire Service Institute, University of Illinois, Urbana, IL, USA; Fire Safety Research Institute, UL Research Institute, Columbia, MD, USA

Shyuan Cheng and Leonardo P. Chamorro, Mechanical Engineering Department, University of Illinois, Urbana, IL, USA

Samuel Vega, Fire Service Institute, University of Illinois, Urbana, IL, USA

Aaron Fields, Seattle Fire Department, Seattle, WA, USA

Dennis LeGear, LeGear Engineering F.D. Consulting, Pleasant Hill, CA, USA

Farzaneh Masoud, Fire Service Institute, University of Illinois, Urbana, IL, USA

Received: 8 August 2023/**Accepted:** 19 December 2023

Abstract. This study investigates the kickback force (F_K) experienced by firefighters during fire suppression using hoses of varying diameters and different nozzle sizes. Rigorous ground tests were conducted, where a fire engine was employed to propel water through a 200 ft hose line, simulating real-life firefighting scenarios while using the hip grip and clamp techniques for hose advancement. Two distinct hose sizes, $1^{3/4}$ and $2^{1/2}$ in., were employed with solid stream nozzles of varying diameters, facilitating the examination of kickback forces at different attacking angles. The findings substantiate that the F_K exhibits variability in response to changes in the attacking angle when utilizing the clamp technique, which encompasses angles of 45°, 30°, and 15°. The 45° angle exhibits the lowest force, while the 30° angle manifests the highest force, demonstrating a notable discrepancy of up to 25% compared to the 45° scenario. The F_K observed at the 15° angle for the clamp technique closely approximates the corresponding values derived from the hip grip hose advancement method. The results also underscore the necessity of regarding the NFPA nozzle reaction force as an integral component of the all-encompassing F_K experienced by firefighters during hose line operations. The NFPA nozzle reaction force resulted significantly below the actual F_K observed in all tested experiments, displaying the most substantial difference of 50% in the case of the 30° angle utilizing the clamp technique.

Keywords: Nozzle reaction, Reaction force, Hose line kickback force, Firefighting hose line, Firefighting nozzle, Firefighter, Fire stream

* Correspondence should be addressed to: Dac Nguyen, E-mail: dacn@illinois.edu



1. Introduction

In the firefighting environment, firefighters utilize hose lines to apply water to hot gases and combusting materials during suppression operations. While managing hose lines through structures with high ambient temperatures and low visibility, firefighters must also counteract the hose line kickback force (F_K) from a flowing hose line. F_K while advancing and flowing fire hose can increase fatigue or injury for firefighters during the training or fire suppression operation. On average 15,130 firefighters per year were injured in handling a charged hose line from 2005 to 2009. Out of 15,130 injuries, 10,775 were minor cases, and 4,355 were moderate to severe cases [1]. From 2010 to 2014, out of 30,290 fire-ground injuries recorded yearly, 24% were sustained by hose line handling [2]. Nozzle reaction force results from a jet action or discharge that is produced by change of momentum due to change in the geometry of the nozzle [3]. Conversely, the hose line kickback force F_K offers a broader perspective on the force experienced by a firefighter. F_K accounts for both the force from water flow acceleration through the nozzle and transmitted through the flexible hose line bend. Various factors, including the characteristics of the hose line, the nozzle size, and the attack angle determine the F_K . The flow force acting on the hose and nozzle results from a change in the flow momentum and the change of pressure as water moves through the nozzle [4, 5]. The change of momentum in the hose line occurs with the convective acceleration of flow at the nozzle due to the discharge's smaller diameter relative to the hose diameter and the change of flow direction due to a bend in the flexible hose line. This occurs because the mass flow rate through any section of the hose line and nozzle must remain constant. As the diameter is decreased, velocity must increase to maintain the mass flow rate of an incompressible range of fluid such as water. The kickback force of the hose line depends not only on the nozzle reaction force, but also on the force due to the hose bend generated by the angle of the hose line and the ground as demonstrated by Vera et al. [5]. In addition, the mass of the water inside the hose section held above the ground also burdens the firefighters' arms as they counteract the force of gravity. Firefighters utilize several techniques to counteract these forces and maintain control of the hose lines during operations.

The National Fire Protection Association (NFPA) [3] provides an example of the forces of water flow applied on the nozzle and the hose section in different directions when a typical hose line attack position is used (Figure 1). It is important to consider both the nozzle reaction force (F_2) and the force on the bending section (F_3) when calculating the F_K that firefighters need to counteract. The force arising from the bending of the hose depends on the angle of the bend.

NFPA [3] provides the suggested model to calculate only the flow force at the nozzle (F_2) as:

$$F_2 = 1.5d^2 \times NP \quad (1)$$

where F_2 is the nozzle reaction force (lbs), NP is the nozzle tip pressure (psi), and d is the nozzle diameter (in.).

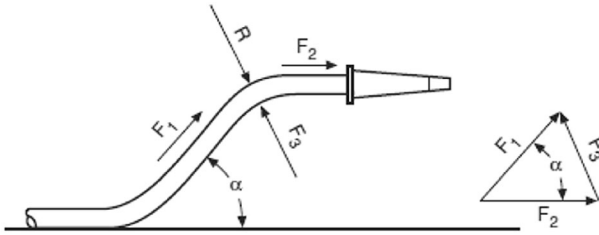


Figure 1. Flow forces acting on the hose line. It is reproduced from the NFPA Fire protection handbook, 20th edition (Figure 13.3.3).

NFPA's formula acts as a model to estimate the force due to the contraction of the nozzle but [3] provides no derivation for this calculation. Despite these limitations, the model to estimate the nozzle reaction force of F_2 is widely accepted and used in fire services in North America [6–9]. There has been some work on the nozzle reaction phenomenon with the effort to derive NFPA model by Chin et al. [6] or optimize the handline flow with minimal nozzle reaction force by Krishnakumar et al. [7] and LeGear [10, 11]. Chin et al. [6] explored NFPA nozzle reaction force model by considering the force on the bend. The final model of Chin's work shows that there is no influence of the bending section on the nozzle reaction force. Textbooks on the firefighting pumping operation include the nozzle reaction force of water flow when determining supply pressure, but without considering the total F_K , such as the force incurred on the hose line at the bend [8].

It is worth mentioning that in studies and observations conducted within the North American fire service, the examination of the hose line F_K frequently focuses solely on the nozzle reaction force, while overlooking the contribution of the force of the bending section. This omission simplifies the calculation process for determining the hose line F_K , but it can result in an underestimation of the force that firefighters need to counteract when operating a charged hose line and nozzle. This underestimation can potentially lead to incidents such as slips, falls, underestimating the number of hose lines needed for fire suppression, or other injuries during hose line operations.

This study comprehensively analyzes the F_K associated with hose lines, considering various attacking angles (hose bend angles) as well as the hose advancement techniques. The investigation includes different nozzle diameters and North America's two commonly used hose line diameters. Additionally, the study examines the flow rate of a hose line configuration with a $2^{1/2}$ in diameter, incorporating a flow meter attached to the inlet hose line.

2. Experimental Method

A series of experiments were run at the Illinois Fire Service Institute (IFSI) training grounds to investigate the F_K with solid stream nozzles of different diameters ($7/8$, $15/16$, 1 , $1^{1/8}$, and $1^{1/4}$ in.) along with varying sizes of attack hoses ($1^{3/4}$ and $2^{1/2}$ in.).

2.1. Testing Apparatus

Two commonly used hose handling approaches were examined during the investigation of hose line advancement and fire attack (Figure 2). The first approach involved using the hip grip technique, where a firefighter, positioned on their knee, secures the hose line against their hip using their hand or arm while the other hand supports the nozzle (Figure 2a). This technique introduces two angles in the hose line: one raises the hose line off the ground (α), while the other angle, (β), redirects it to run parallel to the floor.

In the second approach, called the clamp technique method, the firefighter places their shin over the hose line on the ground, allowing it to pass between their legs while the nozzle is held in hands in front of the body (Figure 2b). The clamp technique introduces only one angle (α), which is the angle generated between the hose line and the ground. The testing apparatus constructed to simulate the hose line angles described above is demonstrated in Figure 3.

The apparatus is comprised of two primary components: the triangular aluminum frame and the nozzle mounting system (Figure 4). The triangle frame (Figure 4a), positioned with the long side lying horizontally, provided support for the apparatus. Two shorter sides of equal length were connected at the top via two pivot points. The front side of the triangle rested on the ground frame at specific stoppage points, while the back side was linked to the ground frame through two pivot points. This design enabled easier adjustment of the desired angle for the two shorter sides of the triangle.

Three angle steps (Figure 4a) provided stoppage points were incorporated to facilitate experimentation, allowing the angle α at the bottom of the triangle to be set at desired angles, 45°, 30°, or 15°. The angle α represents the attacking angle at which the hose line was positioned relative to the ground (Figure 3 b–d). Moreover, the ground frame could be lifted and supported to simulate the hip grip hose advancement position (Figure 3a).

The second component of the apparatus is shown in Figure 4b, which involved mounting the nozzle and a load cell. A 16 in metal pipe, matching the tested hose line's diameter, was used to connect the hose line to the nozzle. The metal pipe was clamped onto a tracking mechanism (sliding plates (blue) on Figure 4b) to move freely along a railing system, which consisted of two sliding rails (green rails on Figure 4b).

An Omega LC01-500 load cell [12] (red piece in Figure 4b) was employed to measure the F_K . This load cell had a measurement capacity of 0–500 lbf and an accuracy of 0.03%. The load cell was securely positioned on the frame between two sliding rails within the same plane as the moving mechanism. The load cell was connected to a computer via a data acquisition system (NI cDAQ-9178 [13]). The LabView environment was used to program the communication between the load cell and a computer and for recording the F_K during the experiments. The data acquisition system was calibrated using several 5 lb counterweights to ensure accurate measurements. Data accumulation was set at a frequency of 100 Hz [12].

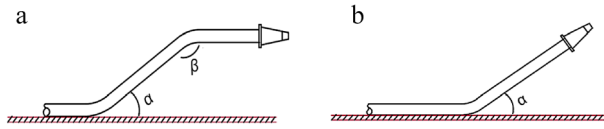


Figure 2. Common fire attacking hose line angles. (a) hip grip position technique generating two angles: α and β , (b) clamp technique, generating only angle α .

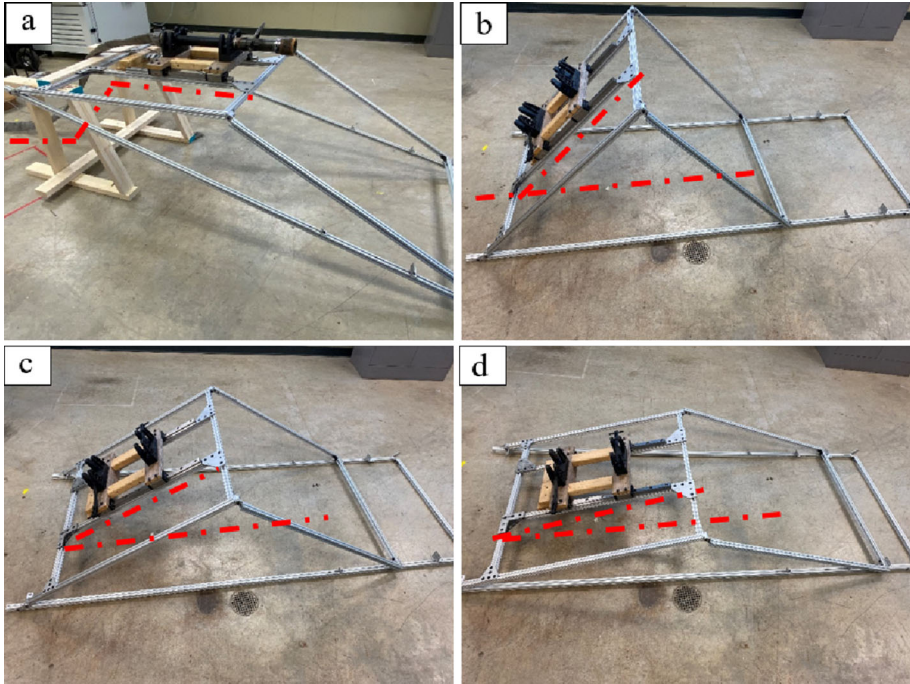


Figure 3. Testing apparatus designed for simulating the F_K associated with hose lines. (a) hip grip position technique, (b) clamp technique 45°, (c) clamp technique 30°, (d) clamp technique 15°. The red dash lines demonstrate the angles associated with each position.

2.2. Experimental Procedure

Experiments were run by a research team at the IFSI training grounds utilizing a fire apparatus. A flow meter, Elkhart EB-500-XD [14], was connected to the intake of the fire apparatus through a 50ft section of 3 in. hose and was supplied water from a fire hydrant with another 50ft section of 3in hose to the flow rate during the testing. The flow meter was calibrated by Elkhart Brass Nozzle & Firefighting Equipment. Tests were run with two assorted hose diameters, including 1^{3/4} and 2^{1/2} in. hoses. Four 50 ft sections of fire hose were connected to simulate typical fire hose deployment scenarios of 200 ft [15]. Different smooth bore

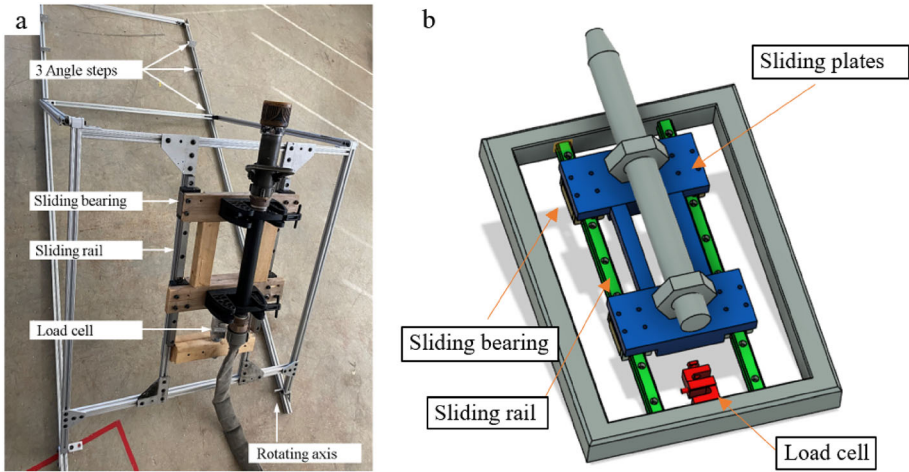


Figure 4. The basic components of the testing apparatus designed for studying the F_K associated with hose lines. The angle steps facilitate convenient change of hose line angle to 45° , 30° , and 15° in clamp technique hose advancing.

nozzle diameters, including $7/8$, $15/16$, and 1 in. were used on $1^{3/4}$ in. hose lines, while $1^{1/8}$ and $1^{1/4}$ in. nozzles were used on $2^{1/2}$ in. hose lines to examine F_K with increased flow rate.

According to NFPA [3] the recommended pressure at the smooth bore nozzle for hand line deployment is 50 psi. Pump discharge pressure at the fire apparatus depends on the pressure loss due to friction incurred in the hose line and the nozzle diameter. Thus, when the pump discharge is located at the same elevation as the nozzle, pump discharge pressure can be calculated as [3]:

$$PDP = NP + FL \quad (2)$$

In the context of fire services, the pressure at the tip of the nozzle (NP) is typically measured using a pitot tube inserted into the flow at a distance equal to half of the nozzle diameter. The nozzle tip pressure (NP) represents the dynamic pressure component in Bernoulli's equation [3]. Here, PDP is the pump discharge pressure (psi), and FL is the friction loss (psi) in the hose line.

From (Eq. 2), the pump discharge pressure at the fire engine with same elevation as nozzle during the experiments can be adjusted and set to be equal to:

$$PDP = NP + FL = 50 + FL \quad (3)$$

The friction loss in the layout can be calculated by $FL = c(Q/100)^2L$ [3], with c as a coefficient based on the hose's diameter and material, L being the hose's length (ft), and Q represents the flow rate (gpm). The flow rate for a hose line can be calculated by knowing the nozzle diameter, d (in), and nozzle pressure by Eq. 4 [3].

$$Q = 29.7d^2\sqrt{NP} \quad (4)$$

The pump operator adjusts the pump discharge pressure to maintain the desired nozzle pressure. This is crucial to ensure efficient and effective firefighting operations. In real-world fireground scenarios, estimating friction loss and determining the appropriate pump discharge pressure relies on techniques acquired through specialized training. These techniques enable pump operators to account for multiple factors, including the hose diameter, hose length, elevation changes, and other resistance effects, allowing them to set the pump discharge pressure for effective firefighting.

2.3. Experimental Procedure for Hose Line of $1^{3/4}$ in

In the initial series of experiments, a $1^{3/4}$ in. hose line and three different nozzle sizes (7/8, 15/16 and 1 in.) were used. The pump pressures employed for each nozzle in the first series of tests were calculated using (Eq. 3) and are provided in Table 1. A total of 3 runs were conducted per condition.

The fire apparatus pump was connected to a standard fire hydrant via a 200 ft long, 3 in. supply hose. The intake flow of water into the pump was measured using an inline flow meter. Prior to collecting experimental data, the entire system was filled with water from the fire hydrant to remove any remaining air in the hose line. The testing procedure for each run proceeded as follow: (1) the frame attack angle was set to 45° and the LabVIEW software was initiated to record the force on the load cell; (2) the pump discharge pressure was adjusted to the calculated value (as listed in Column 2 of Table 1), the discharge valve was opened to supply water to the hose line, and the flow rate was recorded; (3) the water flow was maintained for a duration of 1 min.

Following the completion of tests at the 45° frame attack angle, the frame attack angle was subsequently adjusted to 30° and then to 15° . The same testing procedure was utilized for each attack angle. The test frame was then modified to accommodate the hip grip hose advancement technique by positioning the lifting mechanism underneath the frame (Figure 2a). Three replicates were conducted for each nozzle diameter under these conditions. There was a total of 36 runs for the first series of experiments involving the 1 in. hose line. The pump discharge pressure was set to maintain a nozzle pressure of 50 psi using (Eq. 3).

2.4. Experimental Procedure for Hose Line of $2^{1/2}$ in

In the second set of experiments, a 200 ft hose line with a diameter of $2^{1/2}$ in. was tested using $1^{1/8}$ and $1^{1/4}$ in. nozzle diameters. Similarly, to the first series of experiments, the pump discharge pressure was set based on the calculation of (Eq. 3) to ensure that the NP was equal to 50 psi.

Test conditions with nozzle diameter, pump discharge pressure, and nozzle pressure for $2^{1/2}$ in. hose line are summarized in Table 2. A series of 24 experiments tested the four attack angles and position for $2^{1/2}$ in. hose line. Testing procedures

Table 1
Experimental Parameters for the Tests with 1^{3/4} Hose Line

Nozzle diameter (in)	Pump pressure PDP (Psi)
7/8	130
15/16	155
1	186

Table 2
Experimental Parameters for the Tests with 2^{1/2} Hose Line

Nozzle diameter (in)	Pump pressure PDP (Psi)
1 ^{1/8}	78
1 ^{1/4}	93

for the 2^{1/2} in. hose line follow the same steps in the experiments carried out for the 1^{3/4} in hose line discussed above.

3. Experimental Results

The experimental reaction forces obtained from each run, were analyzed to investigate the F_K firefighters need to counteract in the direction of the attacking water stream. To calculate the actual F_K (lbf), the recorded force (F_r) was adjusted by subtracting the raw measured value of the force (F_0), which was caused by the frame, metal pipe, and a section of empty hose above the load sensor.

$$F_K = F_r - F_0 \quad (5)$$

In real-world firefighting situations, the pump operator responsible for managing the pump during a fire incident will adjust the pump discharge pressure to maintain a nozzle pressure of 50 psi, as tested in this study. As discussed in Sect. 2, this type of pressure regulation was examined for both 1^{3/4} in. and 2^{1/2} in. diameter hose lines. The resulting average real kickback force (F_K) for this particular pressure control method is presented in Figures 5 and 6. It is important to note that experiments for each nozzle, at every angle, were conducted three times to establish the repeatability of the experiments.

Based on this study, the measured F_K varied across different attacking angles, nozzle sizes, and hose diameters. For both the 1^{3/4} in. and 2^{1/2} in. hose lines, a similar trend is observed in changing of F_K as the attacking angle decreases from 45° to 15°. The highest F_K was observed at an attacking angle of 30° across all experimental set ups. The difference between the mean values of F_K between the highest F_K angle (30°) and the lowest F_K angle (45°) was approximately 25%, indi-

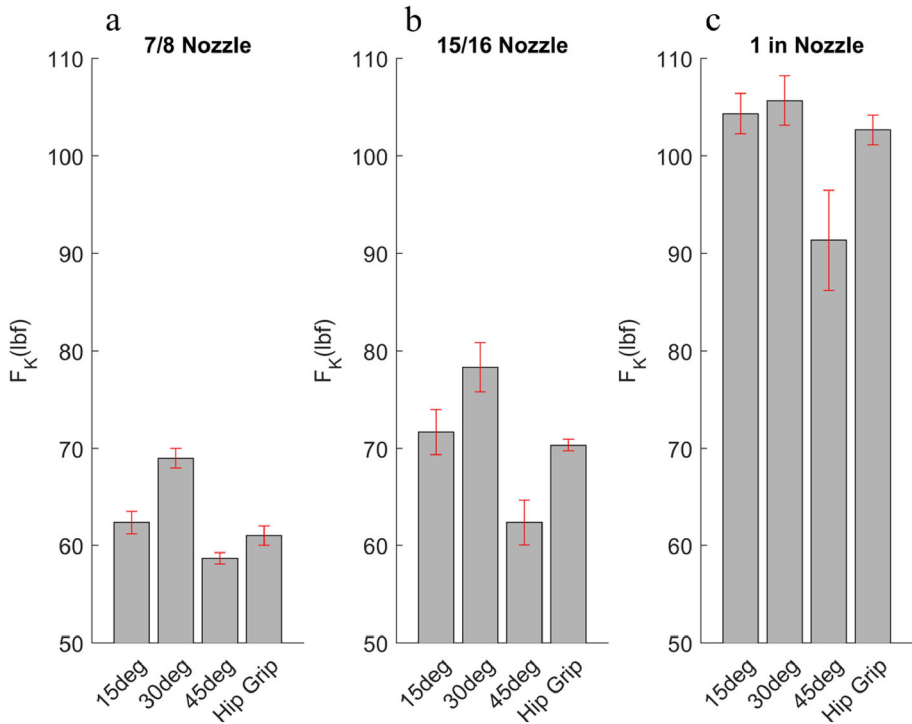


Figure 5. Measured F_K from (a) 7/8 in, (b) 15/16 in, and (c) 1 in. nozzles with $1^{3/4}$ in. hose with different attacking angles and technique. The hip grip presents a hose advance technique indicated in Figure 2a. Regardless of the nozzle size, the 45° angle was lowest across all three experimental designs. The highest F_K was observed at an attacking angle of 30° across all experimental set ups. The F_K using the hip grip method was greater than that observed at 45° using the clamp method. The error bar denotes the standard deviation for each nozzle diameter.

cating that the attacking angle significantly influences the F_K experienced by firefighters.

During the hip grip hose advancement technique, the F_K closely resembled the F_K observed at an attacking angle of 15° in the clamp advancement technique, regardless of the nozzle size. However, some variations depend on the hose diameter and nozzle size. Specifically, for the $1^{3/4}$ in hose line, the F_K using the hip grip method was greater than that observed at 15° using the clamp method. Conversely, for the $2^{1/2}$ in. hose line, the hip grip method resulted in greater F_K compared to the 15° clamp method for both tested nozzle sizes.

The measured F_K experienced in the hose line is a combination of various components, including the nozzle reaction force (F_2 in Figure 1), the force on the bending sections of the hose (a component of F_3 in Figure 1 along the attacking

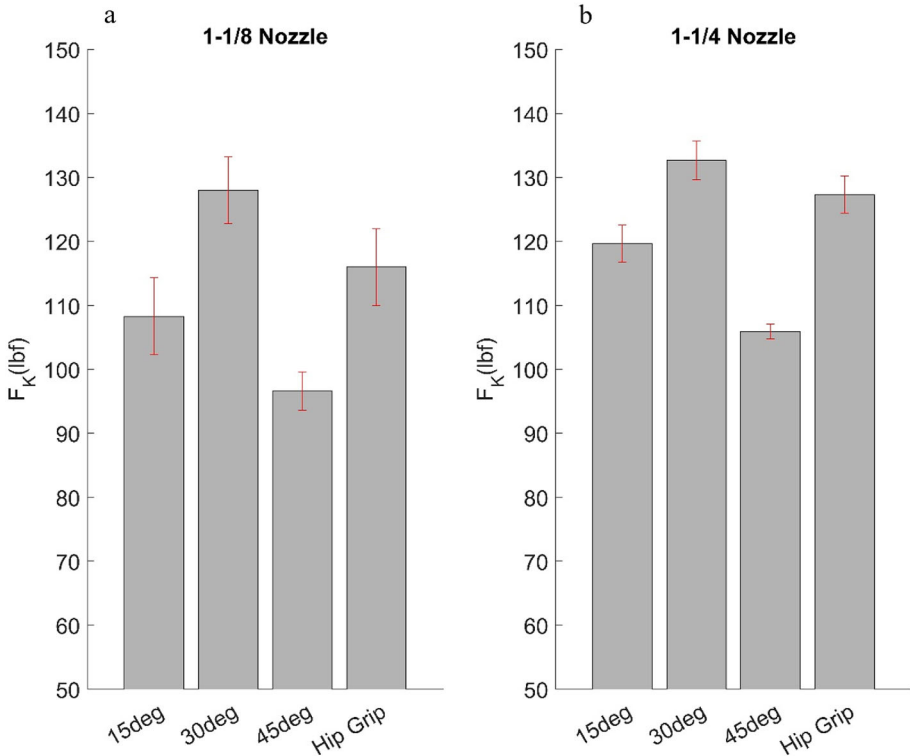


Figure 6. Measured F_K from (a) 1^{1/8} in and (b) 1^{1/4} in nozzles with 2^{1/2} in hose. Hip Grip presents hose advance technique. Regardless of the nozzle size, the 45° angle was lowest across all three experimental designs. The highest F_K was observed at an attacking angle of 30° across all experimental set ups. The F_K using the hip grip method was greater than that observed at 15° and 45° using the clamp method. The error bar denotes the standard deviation for each nozzle diameter.

direction), and the force generated by the mass of water inside the hose. The data collected shows that different bending angles of the hose line result in varying forces acting on the bending sections. The bending angle also affects the contact between the hose line and the ground. This interaction between the hose line and the ground can influence the counteracting force that the ground exerts on the hose line, thereby reducing the overall F_K experienced by firefighters. It is worth noting that the ground counteracting force may explain why the lowest measured F_K is observed at a 45° angle, despite the water mass force being the highest at that angle.

In the comparison between the hip grip technique and the clamp technique at a 15° attacking angle, our study shows that the F_K is greater for the 15° clamp method in the case of the 1^{3/4} in. hose line. We believe that, in the hip grip tech-

nique, there is no force caused by the water mass acting in the attacking direction, as the force due to gravity is perpendicular to the reaction force. However, when considering the 2^{1/2} in. hose line, the high flow rate of water becomes a significant factor. This results in the force exerted on the bending sections of the hose layout in the hip grip technique becoming more dominant than the force caused by the mass of water in the 15° clamp method.

For each testing angle using the prescribed nozzle diameter, tests were run in triplicate to establish the repeatability of the experiments. Table 3 summarizes the coefficient of variation for all tested nozzle diameters. Results indicated high repeatability in the experimental series, with the coefficient of variation ranging from 0.6% to 5%. It can be explained that the reaction force is a function of the nozzle pressure and flow rate. Flow rate, in turn, is a function of nozzle pressure (Eq. 4). Hence, when a specific nozzle diameter and attacking angle are utilized, we can infer that the nozzle reaction force is a variable of nozzle pressure. Here, the nozzle pressure for the repeatability test was kept at the same level by setting the same pressure at the pump. Therefore, we anticipated high repeatability.

The measured kickback forces exhibit variations across different attacking angles. These measured forces include the combined contributions of the force resulting from bending a specific segment of the hose line above the ground and the force resulting from mass of water within that segment. As a result, when applied during actual firefighting operations, the recommended kickback force provided by NFPA [5] in (Eq. 1) may not fully capture the magnitude of the force firefighters need to counteract in order to maintain control of the hose and keep the hose in position. In addition, they may not have adequate hose line for fire suppression.

Figure 7 compares the measured F_K and the NFPA nozzle reaction values for different nozzle diameters when combined with a 2^{1/2} in. hose line. The NFPA nozzle reaction forces were determined by calculating them using (Eq. 1), with the flow rate obtained from the data following the relationship in (Eq. 4):

$$NP = \frac{Q^2}{29.7^2 d^4} \quad (6)$$

The results obtained from Figure 7 provide further evidence supporting the observed F_K variations at different attacking angles (45°, 30°, and 15°) when employing the hip grip technique, as depicted in Figure 5. According to our study, the suggested NFPA nozzle reaction force underestimates the measured F_K for all tested angles and nozzle sizes, with discrepancies reaching as high as 50%. This significant disparity between the measured and suggested values of the nozzle reaction force can be attributed to the fact that (Eq. 1) in the NFPA calculation solely accounts for the nozzle reaction force, while the measured values encompass a combination of the nozzle reaction force, force on the bend, and the water mass. In other words, the discrepancy observed between the measured values reported in this study and the NFPA calculated value primarily stems from the inclusion of the force on the bend and the water mass component acting in the direction of the hose stream.

Table 3
Summary of Coefficient of the Variant of All Experiments

Hose line diameter (in)	Nozzle diameter (in)	COV (%)			
		Clamp 45°	Clamp 30°	Clamp 15°	Hip grip
1 ^{3/4}	7/8	0.83	1.21	1.53	1.33
	15/16	3.12	2.69	2.66	0.67
	1	4.69	1.98	1.64	1.21
2 ^{1/2}	1 ^{1/8}	3.52	1.13	1.92	2.40
	1 ^{1/4}	1.31	1.10	0.85	1.11

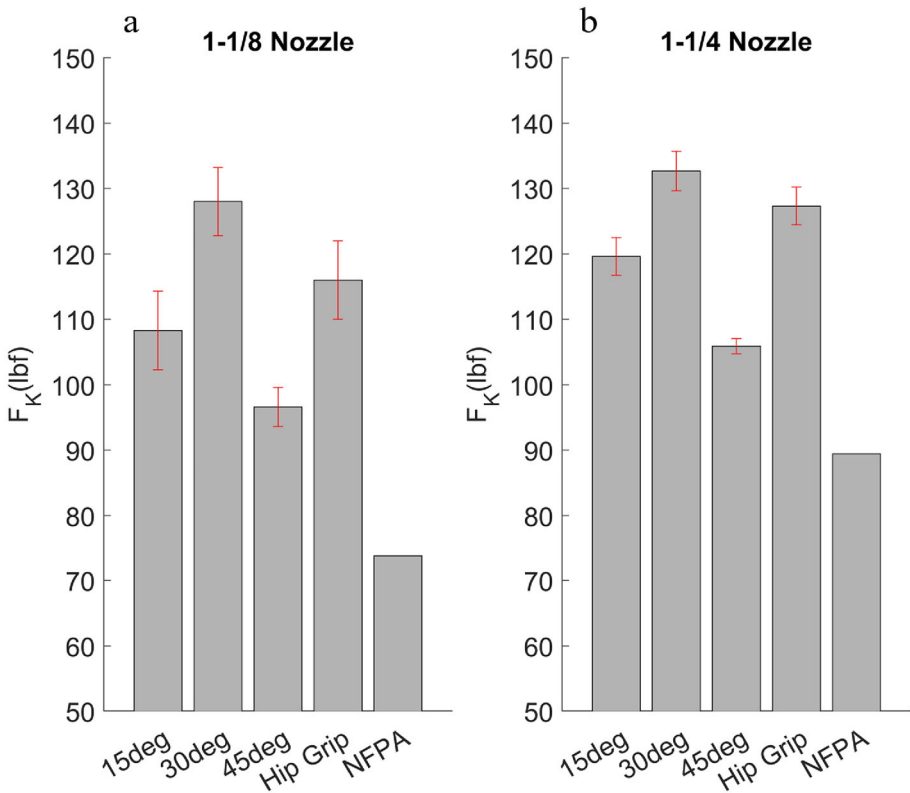


Figure 7. Comparison between actual F_K and NFPA nozzle reaction force from (a) 1^{1/8} in. and (b) 1^{1/4} in. nozzles with 2^{1/2} in. hose. The recommended reaction force provided by NFPA is significantly lower (50%) than the actual force that firefighter experience when bending of the hose and the mass of water parameters are collectively considered. The error bar denotes the standard deviation for each nozzle diameter.

The flow rate of a hose line is an important parameter in the fire service, and (Eq. 4) is commonly utilized to calculate the flow rate for a given nozzle diameter and known nozzle tip pressure which is 50 psi.

The comparison between the measured and estimated flow rates reveals that the measured values are consistently lower, with a range of approximately 10%-15%. This discrepancy can be attributed to the neglect of pressure drop resulting from the reduction of nozzle diameter in the flow rate calculation used by the pump operator. As a result, the pressure employed by the pump operator in the calculation is higher than the actual pressure at the nozzle tip. Consequently, the estimated flow rate tends to be higher than the measured flow rate. This disparity has implications for accurately determining the required number of deployed hose lines in a fire incident.

4. Discussion and Conclusion

The findings in this study emphasize the complexity of the hose line kickback force, F_K , which encompasses the nozzle reaction force, the force due to hose bending, and the force caused by the water mass inside the hose section. The nozzle reaction force alone accounts for only a fraction of the total F_K , typically up to 50%. Relying solely on the nozzle reaction force in fire service practices may oversimplify the force exerted on firefighters, potentially leading to miscalculation of required number of hose lines in a fire incident and severe injuries.

The difference in hose line kickback force across different attack angles, but with consistent nozzle diameters, stems from the differing forces on the bend section, influenced by the bending angle. Notably, the measured hose line kickback force between 30° and 45° cases varies significantly, likely due to the ground's counteractive force. For the 45° case, this counteractive force is stronger than in the 30° scenario, resulting in a reduced kickback force for the 45° angle. The variation in F_K with different hose line attacking angles highlights firefighters' need for careful consideration. Firefighters proficient in handling a hose line at a specific angle may not be adequately prepared to safely operate the hose line at different angles using various hose advancement techniques. Transitioning from a static position with a clamp method at a 45° attacking angle to a dynamic movement with a 30° angle, such as advancing to a new position, can result in a sudden increase in F_K and pose a risk of injury.

The full F_K is crucial when determining personnel roles during hose advancement and suppression operations. Existing recommendations in the fire service suggest that one firefighter can handle a hose line with a reaction force of up to 60 lbs, two crew members for 75 lbs, and three crew members for 90 lbs [16]. However, these recommendations are significantly underestimating the actual F_K experienced by firefighters by 50%.

Alternatively, applying NFPA's reaction force model, LeGear [10] proposed using a larger nozzle size (1^{1/8} in.) on a 2^{1/2} in hose line with lower supplied pressure, rather than smaller nozzle tips (7/8 or 15/16 in.) on a 1^{3/4} in. hose line, to achieve a higher flow rate while maintaining the nozzle reaction force at the same

level as the $1^{3/4}$ in. hose line. However, the omission of pressure drops due to nozzle diameter reduction in estimating pump discharge pressure, solely based on pressure loss along the hose line and nozzle pressure, can lead to an overestimation of the delivered flow rate during a fire incident.

It is important to note that the apparatus used in this study measures the total F_K in the direction of the water-attacking stream. However, it does not encompass the comprehensive stress firefighters experience during hose operating procedures. More study is needed to investigate the perpendicular force that a firefighter needs to apply to the hose line.

Acknowledgements

The authors would like to thank their graduate students, Adrian Zavala, Maddy Szamocki and staff at Illinois Fire Service Institute, Kristen Massey who all assisted with running the experiments. They would also like to thank Elkhart Brass Nozzles & Firefighting Equipment who lent them the flow meter for this study.

Open Access

This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

1. Karter MJ (2012) Patterns of firefighter fireground injuries. National Fire Protection Association, Quincy
2. Campbell R (2018) U.S. firefighter injuries on the fireground, 2010–2014. *Fire Technol* 54:461–477
3. Cote AE et al (2008) Fire protection handbook, 20rd edn. National Fire Protection Association, Quincy
4. Young DF (2011) A brief introduction to fluid mechanics, 5th edn. Wiley, Hoboken
5. Vera F, Rivera R, Núñez C (2015) Backward reaction force on a fire hose, myth or reality?. *Fire Technol* 51:1023–1027. [10.1007/s10694-014-0430-5](https://doi.org/10.1007/s10694-014-0430-5)
6. Chin SK, Jomaas G, Sunderland PB (2017) Firefighter nozzle reaction. *Fire Technol* 53:1907–1917. [10.1007/s10694-017-0661-3](https://doi.org/10.1007/s10694-017-0661-3)

On the Fire Hose Kickback Force in Solid Water Streams

7. Krishnakumar CK, Atallah S, Borows KA (1991) Development of a flow modifier for reducing the reaction force of firefighting nozzles. US Air Force Report ESL-TR-91-301
8. Brakhage C, Miller LA (2015) Pumping apparatus driver/operator handbook, 3rd edn. Fire Protection Publications Oklahoma State University, Stillwater
9. Fornell DP (1991) Fire stream management handbook. PennWell Books, Saddle Brook
10. LeGear DJ (2015) Uncommon thoughts about commonly used suppression equipment: “the missing tip” and optimum handline flow in 2½-inch hose. <http://www.hydrant2nozzle.com/library/2015/12/12/nozzle-dreams>
11. LeGear D. Uncommon thoughts about commonly used suppression equipment: information to aid in the selection of proper handline hose diameter. <https://countyfiretactics.com/wp-content/uploads/2013/11/hose-dreams-11-20-13-final2.pdf>.
12. Stainless Steel S-Beam Load Cells (n.d.) <https://www.omega.com/en-us/force-and-strain-measurement/load-cells/p/LC101>. Accessed 30 Jan 2023
13. c cDAQ-9178. <https://www.ni.com/en-us/support/model.cdaq-9178.html>. Accessed 30 Jan 2023
14. E.B.F. Equipment, EB-500-XD flowmeter (n.d.) <https://www.elkhartsales.com/eb-500-xd.php>. Accessed 30 Jan 2023
15. Avsec R (2020) How much fire hose should a pumper have? <https://www.firerescue1.com/fire-products/fire-apparatus/articles/how-much-fire-hose-should-a-pumper-have-I9LDTtOfHYIF9cWP/>. Accessed 30 Jan 2023
16. Rowett Jr AP (2020) Nozzle knowledge is more than just smooth bore or fog. <https://www.firefighternation.com/training/nozzle-knowledge-is-more-than-just-smooth-bore-or-fog/>.

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.