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Letter to the Editor

Backward Reaction Force on a Fire Hose, Myth or Reality?

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The reader may have noticed a backward force when using a hose, if not, searching the internet for "fire hose car lift" or "flyboard" provides videos of a car or a man suspended in the air by the use of fire hoses. The widely accepted explanation for the backward force produced by a firehose on the firefighters uses Newton's third law in a way that is conceptually wrong. To provide empirical evidence that a backwards reaction force does not exist on a straight hose, we performed a simple experiment that shows that the force produced by water emerging from the nozzle of a straight hose produces a force that stretches the hose. A backwards force appears only when water flows inside a curved hose because water hits the walls of the hose producing a force that is transmitted to the firefighters. The correct application of Newton's laws to understand the forces on a firehose makes it possible to devise new solutions to efficiently fight a fire without having to diminish the water flow to lower the reaction forces in the nozzle. Under this new perspective, it is possible to diminish the forces produced by the nozzle on the firefighters by maintaining the end of the hose as straight as possible and locking the curved hose segments to stationary objects.

In the typical wrong explanation, it is said that the momentum ($\mathbf{p} = m\mathbf{u}$) ejected per unit of time from a hose produces a reaction force or thrust given by: $F = u\, dm/dt$. This is the correct formula to be used for rocket propulsion, where dm/dt is the rate of ejected mass and u is the speed of the ejected water jet. But, this formula can not be used to obtain a reaction force on the nozzle because the nozzle is not propelling water to be ejected out of the hose.

The fire hose example is commonly used when teaching Newton's third law in undergraduate physics courses, but a conceptually correct explanation is very difficult to find [1] and furthermore, it is unknown to the firefighting companies. Although correct calculations for the reaction forces are present in introductory textbooks of fluid mechanics [2], the erroneous explanation is widely disseminated and is present for example in companies selling nozzles, in firefighters training documents, in physics textbooks and physics courses of well known universities. Several examples of this error are shown below:

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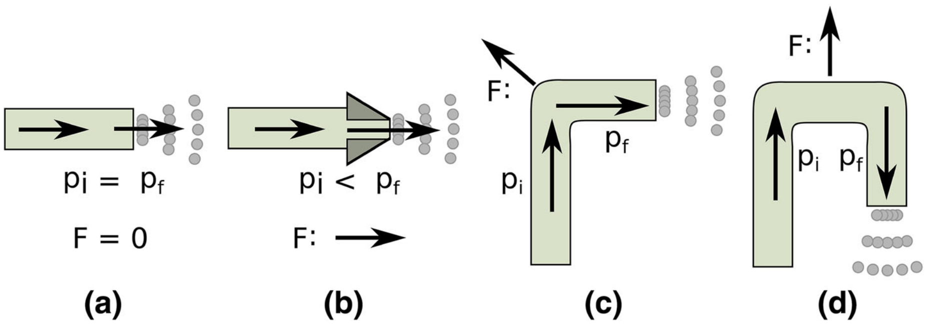

Figure 1. Water momentum *p* and reaction forces *F* produced by water flowing out from different hose geometries.

Example 1 A well known physics textbook explicitly states (Example 9.16: fighting a fire) [3]: "As the water leaves the hose, it exerts on the hose a thrust that must be counteracted by the 600-N force exerted by the firefighters". In this example the authors blindly used the result for the thrust to calculate a non existent backward reaction on the firefighters.

Example 2 The transcription of a video lecture of professor Walter Lewin in a famous course at MIT says [4]: "I remember I had a garden hose on the lawn and I would open the faucet and the garden hose would start to snake backwards. Why? Water squirts out. The garden hose pushes onto the water in this direction. The water pushes back onto the garden hose and it snakes back. Action equals minus reaction". In this example professor Lewin incorrectly applied Newton's third law when he said that water pushes back onto the garden hose.

Example 3 When explaining the firehose instability, professor Sprott, a well known science educator, says in his book "Physics Demonstrations: A Sourcebook for Teachers of Physics" [5]: "If the hose were perfectly straight, the reaction force of the exhausted fluid would be along the axis of the hose and would simply compress it without any sideward motion". In this example professor Sprott is incorrectly applying Newton's third law to explain a non existent compression force instead of the correct forward force on the hose.

Why renowned books and teachers go through this conceptual error without noticing that something is wrong? We believe that the answer lies in the fact that the fluid entering the nozzle 'increases its speed' and, according to Newton's second law ($\mathbf{F} = m\,\mathbf{a}$ or $\mathbf{F} = d\mathbf{p}/dt$), this 'acceleration' must be produced by a force acting on the fluid. Therefore, according to Newton's third law, there should be a reaction force in the opposite direction exerted by the fluid. But, it is the force due to pressure gradients that pushes in the direction of the water flow and the nozzle pushes water in the opposite direction producing a forward reaction force on the nozzle.

This topic has not been properly addressed in the scientific literature and searching in Google "site:.com nozzle reaction force firefighter" produces a large number of links to companies selling firefighting equipment or offering training to firefighters that explicitly mention the wrong concept of a backward reaction force. Even, it is possible to find tables for backward reaction forces for different models of nozzles. Adjusting the nozzle to spray a thinner jet of water makes it possible to obtain a higher water speed and to reach larger distances, but with a lower flux of water and a lower momentum ejected from the hose per unit of time.

Using the simplified models for the geometry of the hose shown in Figure 1, we can easily explain how the change of direction of water momentum causes the backwards force on the firefighters. The arrows shown inside the hose represent the momentum $\mathbf{p}$ of water and the arrows for the force $\mathbf{F}$ represent the net force applied by the jet of water on the hose after changing from its initial momentum $\mathbf{p}_i$ to the final momentum $\mathbf{p}_f$. This force is transmitted to the firefighters producing in some configurations a backward reaction force. For the straight hose shown in Figure 1a there is no change in momentum when the friction with the walls is neglected. Including the nozzle shown in Figure 1b decreases the value of p_i (relative to Figure 1a) increasing the pressure gradient that produces a p_f larger than p_i. The reaction force on the firefighters is directed forwards because the nozzle opposes to the flow of water. For the 90° curve of Figure 1c, the magnitude for the change of momentum per unit of time in the x direction coincides with the value for the momentum being ejected from the hose, and the horizontal backwards force F_x on the firefighter coincides with the typical force calculated using the thrust formula. For the U-shaped hose shown in Figure 1d the magnitude for the change in momentum per unit of time is two times the value of the the momentum being ejected from the hose and therefore the backward reaction force is twice the result obtained using the thrust formula.

We designed a simple experiment using the geometry shown in Figure 1b to provide empirical evidence for a forward reaction force produced by water emerging from a nozzle. A diagram of the experimental setup is shown in Figure 2a and a photograph of the experiment is shown in Figure 2b. In our experiment we measured the elongation of a vertically suspended straight hose as a function of pressure, using an elastic hose inside a fixed transparent plastic hose to prevent bending of the inner hose and to allow it to move freely in the vertical direction. The elastic hose used in this experiment does not intend to emulate a real fire hose, instead it was designed to show in a dramatic way that the hose stretches as the water flows out of the nozzle. To build the elastic hose, we used a twisting balloon (those long cylindrical balloons used to make figures at children parties) and a thin copper wire was wrapped all around the balloon to prevent the balloon from increasing its cross sectional area as a consequence of the inner pressure. A video of this experiment can be watched online [6] and is also available as electronic supplementary material to this letter. The elongation of the hose as a

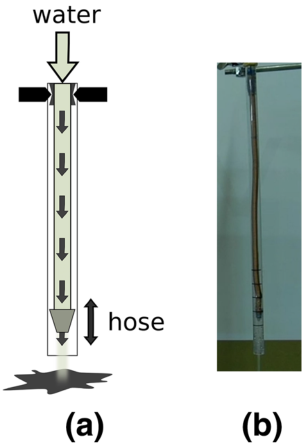

Figure 2. Experiment to show that the water flow produces a force that stretches the hose.

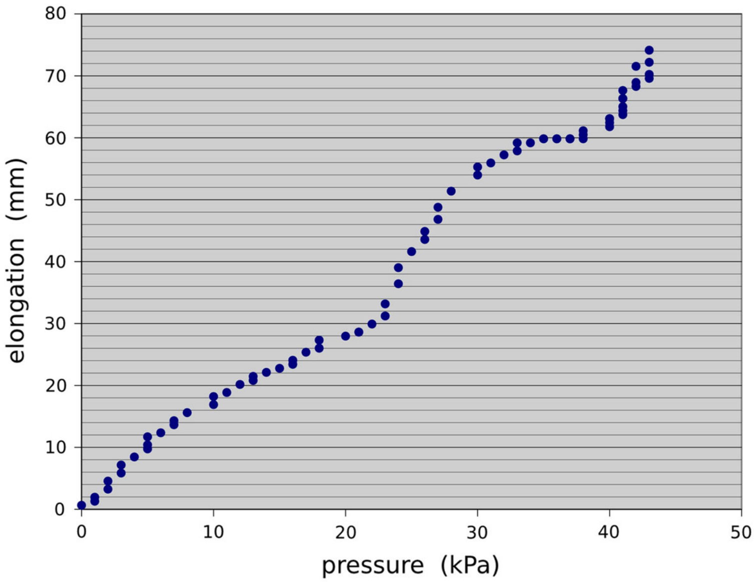

Figure 3. Elongation of a straight hose as a function of pressure.

function of pressure shown in Figure 3 shows that the hose behaves elastically and its length grows with pressure. This experiment confirms the forward reaction force shown in Figure 1b and shows that the known backwards reaction force on the firefighters must be a consequence of a change in momentum of water flowing inside a curved hose end.

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