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J. Fuller, P. Clevely, N. Sowter

Department of Physics and Astronomy, University of Leicester, Leicester, LE1 7RH

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Abstract

In this paper, we investigate the properties known of Greek fire and determine the pressure required to launch a possible substance 15 m, as it was used in close-quarters naval engagements. We find a pressure difference to be 60 kPa above atmospheric pressure, well within the capabilities of the technology the Byzantines had access to.

Introduction

Greek fire was a medieval weapon employed by the Byzantine Empire as either an early type of grenade or, of interest to us, as a pressurised jet of liquid fire. It saw use in naval combat [1] where it is recorded to have remained burning even when in contact with water [2]. The recipe was lost to time, with modern historians proposing several possible formulae, the most accepted today being a mixture of crude oil and resins [3]. In this paper, we investigate the thermal properties of Greek fire using a simple model with some assumptions and estimate the required pressure that the jet of fire would need to be effective in a naval battle, based on possible material properties.

Method

The most notable characteristic of Greek fire is that it continued to burn in water [2]. To model this, we consider the heat flux of the system:

$$\dot{m}\Delta H_c \geq L \tag{1}$$

Where $\dot{m}\Delta H_c$ is the produced heat flux, with $\dot{m}$ being the mass burn rate of the fuel, ΔH_c is the specific heat of combustion for the fuel [4], and L is a loss term accounting for all the heat flux acting to cool the system while in contact with water. We have imposed the condition that for the fire to continue burning, the net heat flux must be greater than 0.

The primary path of heat loss in the system is through conduction into the water, with contributions due to convection and radiation to the atmosphere. Where convection is insignificant compared to the dominating conduction term, the heat loss factor can be expressed in terms of conduction and radiation [5]:

$$\begin{aligned} L &= \frac{\kappa_w(T_{fire} - T_{water})}{d} + \epsilon\sigma(T_{fire}^4 - T_{atm}^4) \\ &= \dot{q}_{condution} + \dot{q}_{radiation} \end{aligned} \tag{2}$$

Where κ_w is the conductivity of water, d is the thickness of the thermal boundary between the fire and the water, and T are the relevant temperatures. ϵ is the emissivity of the fire, which we assume to be 0.8, and σ is the Stefan-Boltzmann constant.

Combining Equations 1 and 2, we can estimate the threshold heat of combustion to continue burning:

$$\Delta H_c = \frac{1}{\dot{m}} \left(\dot{q}_{conduction} + \dot{q}_{radiation} \right) \qquad (3)$$

κ_w and σ are well known constants [6], we assume the atmosphere to have a temperature of approximately $T_{atm} = 300\,\mathrm{K}$ and that near the interface with the fire, water will be near the boiling point $T_{water} = 373\,\mathrm{K}$, where the boundary layer is approximated as $d = 1\,\mathrm{mm}$. Based on modern recreations of the Greek fire [3], we estimate the fire to have a temperature $T_{fire} = 1000\,\mathrm{K}$.

We take an estimate burn rate as $15\,\mathrm{g\,m^{-2}\,s^{-1}}$ from which we determine that $\Delta H_c \geq 28\,\mathrm{MJ\,kg^{-1}}$. This value was compared to those of common fuels [4] and their densities [7]. For fuels with similar ΔH_c values, an average density of $\rho = 850\,\mathrm{kg\,m^{-3}}$ was determined. This is less dense than water and, as expected, can float and burn on top.

Application

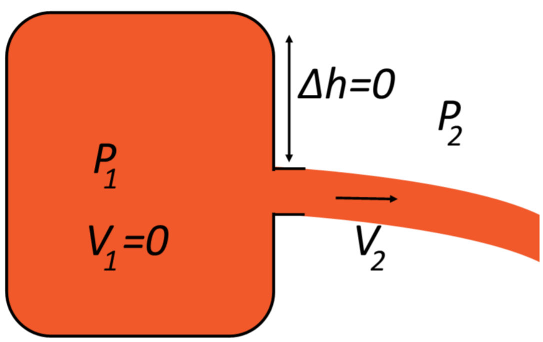

Figure 1: Diagram of the pressurised container with a nozzle. P_1 is the internal tank pressure, V_1 is the internal fluid speed, P_2 and V_2 are the external pressure and fluid speed respectively.

A noted deployment of Greek fire was during naval battles, where it was spurted out of pressurised containers to light the enemy ships on fire [1]. We first consider the exit velocity v the substance would require to hit a target at some distance R, assuming negligible drag forces and constant vertical acceleration [6]:

$$v^2 = \frac{Rg}{\sin(2\theta)} \qquad (4)$$

Where g is gravitational acceleration and θ is the angle of the exit stream relative to the horizontal. We assume ideal conditions $\theta = 45°$ such that the range is maximised for a given exit velocity.

Using the exit velocity, we can then estimate how much the container must be pressurised using the Bernoulli equation [6]:

$$P_1 + \rho g \Delta h + \frac{1}{2}\rho v_1^2 = P_2 + \frac{1}{2}\rho v_2^2 \qquad (5)$$

Where $v_2 = v$ is the exit velocity of the fluid, and we assume that the height difference between the top of the container and the nozzle is negligible, $\Delta h \approx 0$, as is the fluid speed in the container $v_1 \approx 0$, and that P_2 is simply the atmospheric pressure. The pressure difference $\Delta P = P_1 - P_2$ is how much the container must be pressurised. Using these simplifications, we combine Equations 4 and 5 to find the required pressure in terms of the required firing range:

$$\Delta P = \frac{\rho R g}{2\sin(2\theta)} \qquad (6)$$

Discussion & Conclusion

From Equation 6 we find that for a conservative estimate for the range of $R = 15\,\mathrm{m}$, the container would require a pressure of $60\,\mathrm{kPa}$ above atmospheric pressure. Modern wooden barrels are tested to withstand up to $200\,\mathrm{kPa}$ [8], which is a reasonable assumption of the technology capabilities of the Byzantine empire. The vessels containing the fire are claimed to be made from bronze [2], which is likely to have a better pressure capability than a wooden barrel. We conclude that the pressure limitations are possible for the technology of the time.

We have applied a simple model in this paper to obtain first-order estimates for the capabilities of Greek fire. This includes the assumption that convection is insignificant when compared to the heat loss of the fire through conduction and radiation, and that the rate of heat change is steady with time. We also assume that drag is an insignificant factor, as it has been recorded that Greek fire was only deployed when conditions were calm with no wind [1].

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