The Mirror Weapon in Archimedes Era

A.S. Papadogiannis, N.S. Papadogianni, A. Carabelas, S. Tsitomeneas, P. Kyraggelos and T.G. Chondros

Abstract The historical accounts of Archimedes' war-faring inventions are vivid and possibly exaggerated. It is claimed that he devised catapult launchers that threw heavy beams and stones at the Roman ships, burning-glasses that reflected the sun's rays and set ships on fire. It is said that Archimedes prevented one Roman attack on Syracuse by using a large array of mirrors (speculated to have been highly polished shields) to reflect sunlight onto the attacking ships causing them to catch fire. In this paper the parameters of irradiation intensity produced by burning glasses or mirrors are investigated and compared with experimental results from the literature.

Keywords Burning glass · Mirrors weapons · Solar irradiation · War machines · Experiments

Introduction

The first known written record of the word "machine" appears in Homer and Herodotus to describe political manipulation [1, 2]. A remarkable mechanism, the first device for which the name mechane (machine, in Greek, Deus ex machine in Latin) is used, is the one used extensively in the ancient Greek theatre in Aeschylus times (4th century BC) as a stage device to lift actors, chariots or flying horses in the air, as though flying, portraying the descent of gods from the sky and similar purposes. They were large mechanisms consisting of booms, wheels, and ropes that could raise weights perhaps as great as one ton and, in some cases depict space travel [3].

Archimedes systematized the design of simple machines and the study of their functions. He invented the entire field of hydrostatics with the discovery of the Archimedes' Principle. Archimedes studied fluids at rest, hydrostatics, and it was nearly 2000 years before Daniel Bernoulli took the next step when he combined

A.S. Papadogiannis (✉)
University of Patras, Department of Mechanical Eng. & Aeronautics, 265 00 Patras, Greece
e-mail: papadog@mech.upatras.gr

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Archimedes' idea of pressure with Newton's laws of motion to develop the subject of fluid dynamics [4–6]. He made many other discoveries in geometry, mechanics and other fields and introduced step-by-step logic combined with analysis and experiments in solving mechanical problems and design of machinery procedures.

Archimedes was also known as an outstanding astronomer; his observations of solstices were used by other astronomers of the era. As an astronomer, he developed an incredibly accurate self-moving model of the Sun, Moon, and constellations, which even showed eclipses in a time-lapse manner. The model used a system of screws and pulleys to move the globes at various speeds and on different courses [7].

At the time of Archimedes Syracuse was an independent Greek city-state with a 500-year history. The colony of Syracuse was established by Corinthians, led by Archias in 734 BC. The city grew and prospered, and in the course of the 5th century BC the wealth, cultural development, political power and victorious wars against Athenians and Carthagenians, ensured for a long time the dominance of Syracuse as the most powerful Greek city over the entire southwestern Mediterranian basin [4].

During Archimedes' lifetime the first two of the three Punic Wars between the Romans and the Carthaginians were fought. The series of wars between Rome and Carthage were known to the Romans as the "Punic Wars" because of the Latin name for the Carthaginians: Punici, derived from Phoenici, referring to the Carthaginians' Phoenician ancestry.

During the Second Punic War (218–201 BC) – the great World War of the classical Mediterranean, Syracuse allied itself with Carthage, and when the Roman general Marcellus began a siege on the city in 214 BC, Archimedes was called upon by King Hieron to aid in its defence and Archimedes worked as a military engineer for Syracuse [4].

The historical accounts of Archimedes' war-faring inventions are vivid and possibly exaggerated. It is claimed that he devised catapult launchers that threw heavy beams and stones at the Roman ships, burning-glasses that reflected the sun's rays and set ships on fire, and either invented or improved upon a device that would remain one of the most important forms of warfare technology for almost two millennia: the catapult. Plutarchos and Polybios (201–120 BC) describe giant mechanisms for lifting ships from the sea, ship-burning mirrors and a steam gun designed and built by Archimedes [4].

Archimedes discoveries in catoptrics are reported [7, 8]. It is said that Archimedes prevented one Roman attack on Syracuse by using a large array of mirrors (speculated to have been highly polished shields) to reflect sunlight onto the attacking ships causing them to catch fire. This popular legend has been tested many times since the Renaissance and often discredited as it seemed the ships would have had to have been virtually motionless and very close to shore for them to ignite, an unlikely scenario during a battle. Tests were performed in Greece by engineer Sakas in 1974 [8] and by another group at MIT [4] in 2004 and concluded that the mirror weapon was a possibility.

The solar irradiation is photon energy **W**, is inversely proportional to the wave length λ in vacuum:

$$W = \frac{h.c}{\lambda} \cong \frac{2}{\lambda(nm)} \cdot 10^{-16} \quad (1)$$

Optical wave energy is subject to high degradation during reflection on materials or during diffusion in the atmosphere. Mirrors possibly consisting of polished shields made of bronze, capable of reflecting sun-rays provided a warfare mechanism in classical antiquity [4]. The dimensions and the optical parameters of the mirror surfaces as well as the degrees of freedom for targeting were crucial factors for their configuration and arrangement according to the specific needs, sufficiently determining the effectiveness of the mechanism. Knowledge of the solar irradiation parameters is an important factor, for the design of the mechanism and the the mirror's surface characteristics. In Fig. 1 the solar radiation vs. the wave length is shown.

Then a supervising practical medium should be set up to ascertain its effectiveness, and thus the investigation and analytical knowledge of the local parameters will proceed. The relevant procedure should have been supported with data for the adequate calculation of the direct sun irradiance that will fall on the mirror. In the past experimental observation must have been used. The sun's irradiance **E** on the mirror depends on the sunlight spectral irradiance $\mathbf{E}_\lambda$ at wavelength λ as:

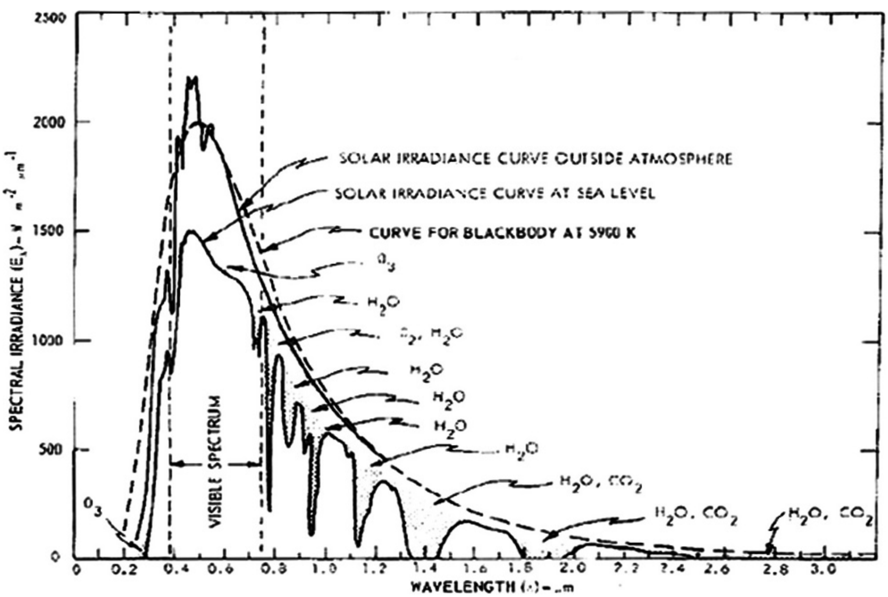

Fig. 1 Solar radiation on Earth's surface (NASA/ASTM standard)

$$E = \int_0^\infty E_\lambda d\lambda \quad (2)$$

Outside the earth's atmosphere the solar irradiance is: $E \cong 1400 W/m^2$ at perihelion. $E = 1353\ W/m^2$ is accepted by NASA [9, 10] as the solar constant at the mean Earth–Sun distance. Therefore, this value may be used as the level of the optical input energy unfiltered by the atmosphere. Under the same conditions the mean E_λ curve given by NASA/ASTM standard is more useful (Fig. 1). The influence of the atmospheric absorption on the sun's irradiance over the earth's atmosphere, is given by the Bouguer-Lambert law, yielding the mean S_λ intensity of the immediate irradiation on the earth's surface at wavelength λ as:

$$S_\lambda = S_{0\lambda} p_\lambda^m \quad (3)$$

where $\mathbf{S_{0\lambda}} = \mathbf{H}$, the solar irradiation intensity entering the earth's atmosphere, $P_\lambda = 0$ the (spectral) atmospheric absorption coefficient depending on the molecular absorption and diffusion in the atmosphere, and m=H the atmospheric optical air mass depending on the angle β of the solar rise (Fig. 2), as:

$$m = 1/\sin\beta \quad (4)$$

As a result, the direct sun irradiation will be at its minimum in the morning and maximum at noon time, while during the rest hours of the day the average values will depend on the atmospheric optical mass. This general daily course will also be

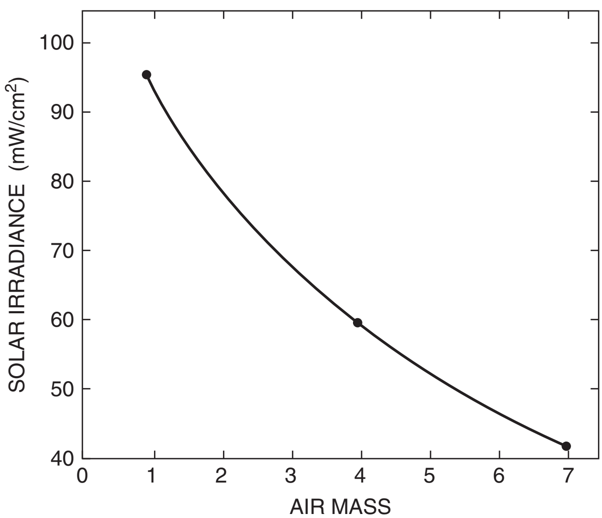

Fig. 2 Air mass and solar radiation

shaped by the local light diffusion or absorption by the clouds, suspension of dust particles etc., which have a share in the atmosphere transparency.

Solar Beam Irradiation Properties

Intensity is the main feature of the solar beam, ensuring controllable applications on a target, with maximal impact on the tissue of a body or flammable organic object. Biological effects from optical irradiation also depend on wavelength; therefore, the results depend on the surface material of the mirror and the reflection value of solar spectrum from the near – IR through to the UV. Main parameters influencing solar beam irradiation are: (i) the irradiation duration, (ii) the relaxation time (the duration over which the tissue or organic object loses half of the absorbed energy). Therefore, interaction depends on the irradiation type, the mechanical and thermal characteristics (emissivity and conductivity) and the size of a target. The optimal use of solar beam with maximal damage (trauma to tissue, flame on objects) depends on the relation between duration and relaxation time.

The radiation absorption of a target depend mainly on its water content (skin 70%, bone 10–30% etc.), modified by the content of blood, chromophores etc. Light absorption depth L is the inverse of the absorption coefficient a ($L = 1/a$). Water has several absorption ($a = 13000$ cm^{-1} at 2.8 μm, $a = 50$ cm^{-1} at 2.1 μm, $a = l$ cm^{-1} at 1.06 μm) and transmission peaks (the largest almost 400 nm). Blood is a strong absorber of visible light (several peaks in 400–600 nm). Chromophores modulate absorption in the visible spectral region (melanin's $a = 1000$ cm^{-1} at 400 nm and $a = 80$ cm^{-1} at 1 μm), followed by the protein's absorption ($a = 27000$ cm^{-1} at $\lambda < 200$ nm). Therefore, the final impact is mainly based on the wavelength and duration time combination. Thus, the mirror type (wavelength, power output) is constructed to optimize the interaction with the targeted tissue/object and the beam-target interaction. In any given case, the optical radiation optimization depends strongly upon the reflection characteristics of the mirror which is being used [9].

The solar radiation beam effects upon a target may be categorized as (i) non-thermal (tissue is photo-stimulated or heated to approximately 62°C) in a photomechanical process, and to (ii) thermal (tissue/object is heated to approximately above 62°C) in a coagulation, vaporization, and carbonization process. Photomechanical interaction to the tissue is produced by a high power moving beam focused into a small spot. An optical breakdown may occur with the production of momentary localized ionized plasma in multiphoton processes. The hydrodynamic shock wave following the plasma formation can disrupt tissues (semitransparent membranes etc.). If a tissue is heated below 62°C (reversible warming at 35∼55°C, fuse of collagen fibers at 55∼62°C) the thermal damage is confined to the mechanical disruption region. The photochemical interaction is the optically triggered-accelerated chemical process in the tissue, with final ult a different chemical structure. Coagulation is the blanching of the photo-irradiated tissue caused by the structure change which leads to an increased scatter and multiple refraction/reflection of illumination light, as the temperature is raised up to 62∼100°C. The main coagulation mechanism is protein (collagen etc.) denaturation, when the molecular form the ubiquitous protein becomes unstable and the chains unfold. In the vaporization process, the tissue is heated to 100°C, thus cell water boils and steam escapes from the ruptured explosive cell walls. The tissue/object damage, by the steam spread of heat, is limited in the absorption area of an optical beam. Once water has completely evaporated from a cell and irradiation is continued, any debris remaining in the ruptured structure and the residual material is rapidly raised to a higher temperature. At 300–400°C the tissue/object becomes carbonized (blackens) with outgas and smoke, and at over 500°C it burns and evaporates in the atmospheric oxygen.

The quantification of the solar beam potentia1 harm is done according to Laser beam impacts [9] depending on the wavelength and power output. The beam is non-harm, inherently, due to the low output beam power by which it cannot exceed the ocural Exposure Limit level [11, 12]. If a mirror emits low power ($maxP_o$<lmW) in the 400–700 nm region, human aversion to bright light will protect the enemy personnel. Thus a protection mechanism is the eye's 0.25 s "blink reflex". If a mirror emits slightly higher-power (1 mW < $maxP_o$ < 5 mW) in the 400–700 nm region, then the direct viewing of the beam dangerous, and the blink reflex is the primary protection. If a mirror emits medium power ($maxP_o$ < 500 mW) and does not belong to the previous cases, then it produces direct hazardous emissions, and the diffused beam reflection is not hazardous unless a person stares on it intentionally. If the mirror emits high power ($maxP_o$ > 500 mW), it produces direct and diffuse, irradiation.

Any exposure above the Exposure Limits expressed as irradiance E (in W/m^2 or mW/cm^2) or radiant exposure H (in J/m^2 or mJ/cm^2) would be a damage risk [13]. The simplest over-exposure of the eye to a solar beam reflected by a mirror for $400 < \lambda < 1400$ nm may cause retina damage. Since there may be no pain or even discomfort when a beam strikes the retina, the victim may not be aware of any injury until several burns have been infected and vision has been impaired. The injury effects are thermal and/or non-thermal [7, 9]. Beams with wavelength beyond the 400–1400 nm region and not focusing onto the retina, are absorbed at the cornea or skin with other damage mechanisms involved.

The nominal hazard zone (R_{NHZ}) gives the possible over-exposure range. Numerical examples of optical radiation hazard given in the next table with the use of the formula [15–17].

$$R_{NHZ} = -\frac{1}{\tan(\frac{\Phi}{2})}\sqrt{\frac{knP_O}{\pi S_{EL}}} \tag{5}$$

Table 1 Nominal hazard zone range (RNHZ) in a beam from n mirrors with concentration k & divergence 0,05 rad reflected at n elements with appropriate mirror surface of 1 m^2

Wavelength band nm	Reflectivity	Power output W	Exposure duration s	Personnel R_{NHZ} m	Wood R_{NHZ} m
400–520	0,4	Kn.66,7	0,25	$36,5\sqrt{kn}$	$3,65\sqrt{kn}$
750–1400	0,9	Kn.292,1	10	$121,4\sqrt{kn}$	$12,14\sqrt{kn}$

where Φ = the beam divergence (rad), P_o = the power output from one mirror (Watts), n = the number of mirrors with concentration k, and S_{EL} the appropriate exposure limit (W/m^2).

It is clear that in all these cases of caustic mirrors the explosure must be higher than the exposure limits. Thus the nominal hazardous zone (R_{NHZ}) gives the possible over-exposure range.

Conclusion

Archimedes discoveries in catoptrics are reported [8, 18, 19]. The historical accounts of Archimedes' war-faring inventions are vivid and possibly exaggerated. It is claimed that he devised catapult launchers that threw heavy beams and stones at the Roman ships, burning-glasses that reflected the sun's rays and set ships on fire, and either invented or improved upon the catapult. It is also said that Archimedes prevented one Roman attack on Syracuse by using a large array of mirrors (speculated to have been highly polished shields) to reflect sunlight onto the attacking ships causing them to catch fire. This popular legend has been tested many times since the Renaissance and often discredited as it seemed the ships would have had to have been virtually motionless and very close to shore for them to ignite, an unlikely scenario during a battle. But, recently tests were performed in Greece by engineer Sakas in 1974 [8] and by another group at MIT in 2004 and concluded that the mirror weapon was a possibility. A theoretical investigation on the sun-rays properties presented here may be used as an evaluation tool for supporting this theory and can be further extended to various mirror and sunglass configurations.

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