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Analytical and innovative solutions for heat transfer problems involving phase change and interfaces

The eponymous, anonymous Joseph Stefan

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ABSTRACT

A brief biography of the Austrian/Slovenian physicist Joseph Stefan is given, along with an outline of some of the most notable work he did at the University of Vienna including radiation heat transfer and solid–liquid phase change.

1. Introduction

The Stefan–Boltzmann constant *and* equation; Maxwell–Stefan diffusion; The Stefan number; a law, a problem, a flow and a force. Eponymous? Absolutely. Anonymous? Not for long.

Joseph Stefan (Fig. 1) was born on March 24, 1835 in Klagenfurt, then part of the Austro-Hungarian Empire. Today, it is the capital of the Carinthia region of Austria, not far from the border of Slovenia, formerly one of the federated states Yugoslavia. It was a teeming trading center and market town, situated on a beautiful lake, the Wörthersee. It also had a large ethnic Slovene population, two of whom were Aleš Stefan and Marija Startinik, Joseph's parents. Stefan grew up a precocious child, proud of his Slovene heritage, prone to poetry and talented in his studies, so much so that he surpassed his teachers in his math and science abilities. After seriously considering joining the Benedictine order to become a priest, he instead studied physics at the University of Vienna with monk-like devotion. Soon after receiving his doctorate, a fortunate opportunity arose and in 1865, at the tender age of 30, he became Director of the University's Institute of Physics, and remained in that position until his death in 1893 [1]. One of his first students was the young, gifted Ludwig Boltzmann. The difference in age was a mere nine years, but the student–teacher relationship was to have a lasting impact on the history of modern physics.

2. Radiation heat transfer; the T^4 law

Not long after Boltzmann left the Institute of Physics in Vienna to take a position in Graz, Stefan began to look at data relating the amount of energy transferred by radiation and the temperature of the receiving surfaces. It was known at the time that radiant energy was not a linear function of the temperature, and in fact, increased quite drastically as the temperature increased. However, the relation between the radiant energy and the temperature was not known. In 1817, Dulong and Petit [2] published results from experiments they performed using a spherical bulb in a spherical chamber, and proposed a model for the radiant energy as a function of the temperature to be,

$$E(T) = \mu a^T \tag{1}$$

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Nomenclature

a	constant	T	temperature . . . . . K
c_p	specific heat . . . . . kJ/kg K	μ	material constant
E	emissive power . . . . . W	λ	latent heat of fusion . . . . . kJ/kg

Fig. 1. Portrait of Joseph Stefan, taken around 1885.

Wählt man für das Gesetz der Strahlung die Formel der vierten Potenzen der absoluten Temperaturen, so ist

$$H_1 = AT_1^4, \quad H_2 = AT_2^4$$

Fig. 2. First appearance in print of the T^4 radiation law.

where μ was a constant dependent on the size and material of the body, $a = 1.0077$, and T was the temperature in degrees Centigrade. After analyzing the Dulong and Petit data, Stefan did not feel comfortable with their model and began to look at other relations to fit the data better. He also investigated in detail their experimental set-up and realized that there were significant losses due to conduction in the spherical bulbs. After making adjustments in the data, Stefan proposed a model, published in 1879, and using his original notation gave the formula [3] shown in Fig. 2, where, "A depends on the size and the surface of the body," which fit the data quite well. This is the origination of the famed T^4 radiation law, named for Stefan, and later his student Boltzmann. Why Boltzmann? When first published, Stefan's T^4 law was not particularly well-received by the scientific community. In Graz, Boltzmann treated the radiation as gas particles and using thermodynamic principles, derived the T^4 law. This validated Stefan's work, and the relation given in Fig. 2 has since been known as the Stefan–Boltzmann law. The story doesn't end there. Boltzmann's treatment of the kinetic theory of gases, as well as his work on the radiation law inspired Wilhelm Wien to develop radiative energy distributions, which in turn motivated Max Planck to derive relations which became the foundation of quantum mechanics.

3. Solid–liquid phase change

In the mid-1800s, the seafaring nations of Europe were determined to find the so-called "Northwest Passage" through the Arctic in order to reduce shipping time to India and the Far East. As a Secretary and Vice-President of the Austrian Academy of Sciences, surely Stefan knew of the voyages and had access to the scientific data they produced. From 1872 to 1874, the Austro-Hungarian Empire sponsored an expedition to the polar ice caps [4]. During this trip, they took air temperature measurements, and recorded ice growth rates. The leader of the expedition, Karl Weyprecht and co-leader Julius von Payer reported their findings to the academy in 1876. With their data in hand, Stefan attempted to find an analytical solution to this moving boundary problem. Earlier investigators had worked on this problem, but due to slow dissemination of scientific results, Stefan did not know of their work. Stefan began his analysis by using a conservation of energy model at the solid/liquid interface and assuming a linear temperature profile within the ice. He showed from this simple model that the square of the ice thickness was a linear function of time. Using this model, Stefan compared his

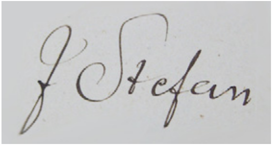

Fig. 3. Joseph Stefan's signature.

theory with the experimental data and found rough agreement between the two [5]. Valid comparisons were hampered by the fact that there were not accurate values for the thermal conductivity of ice. However, Stefan was encouraged that his simple model did match the trends of the data. After Stefan published his paper, the solid/liquid phase change problem lay dormant for many years. It wasn't until about a half-century later that researchers became interested in the problem again, and to honor Stefan's work, the solid/liquid phase change problem or moving boundary problem was called the Stefan problem. The Stefan problem, and variants of it, have been an active and fruitful area of research ever since. The primary dimensionless number in these types of problems is the Stefan number,

$$Ste = \frac{c_p \Delta T}{\lambda} \tag{2}$$

where c_p is the specific heat, ΔT the temperature difference, and λ the latent heat. This ratio was coined by Lock [6] when he used it as a perturbation variable in an asymptotic, approximate solution to the moving boundary problem.

Besides the radiation and phase change work mentioned here, Stefan also contributed to areas such as the measurement of thermal conductivity of gases, evaporation, fluid diffusion, electromagnetics and optics, among others.

When Stefan died of a stroke in 1893, he had put a then-hardly recognizable stamp on science. Since then, his name (Fig. 3) has been associated with a broad range of technical fields. Few scientists have been so eponomically connected to physical phenomena, yet are so anonymous to modern-day researchers. He lies buried in a grave in Vienna's famed *Zentralfriedhof*, not far from his student Boltzmann and his famous headstone. Sadly, Stefan's plot remained uncared for, and the grave was reused not once, but twice. And so the eponymous Stefan rests, anonymously for the ages.

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