Rankine's Scientific Work, Vision on the Bicentenary of His Birth

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Abstract: - **The bicentennial of the William John Macquorn Rankine will be commemorated in July 5, 2020. He is known as Rankine in scientific and academic circles and was a British-born Scottish polymath that worked in civil, mechanic and marine engineering sectors. Thermodynamics was founded using their scientific work together with Rudolf Clausius and William Thomson studies. From 1842 he published hundreds of articles and notes on science and engineering. With multiple interests, he studied many subjects like botany or music theory, using the branches of mathematics, science and engineering.**

***Keywords*: Rankine, Engineering, Thermodynamic cycle**

I. SMALL RANKINE BIOGRAPHY

William John Macquorn Rankine, son of David Rankine and Barbara Rankine, was born in Edinburgh, Scotland on July 5, 1820 and died in Glasgow (Scotland) on December 24, 1872, at 52 years old. Rankine, due to his poor health, was initially educated at home. From 1928 to 1929, he attended for a very short time, the Ayr Academy at Glasgow High School. Around 1830, the family moved to Edinburgh, and in 1834 began study at the Naval Academy with the mathematician George Lees. After returning to Edinburgh, he began working as army engineer , on the Edinburgh and Dalkeith Railway. In 1855 was appointed professor of civil and mechanical engineering at the University of Glasgow, remaining in this post until, his death on December 24, 1872. Rankine was a British-born Scottish polymath who worked in the civil engineering sectors, assisting in mechanical and marine engineering, as well as physical engineering. One of Rankine's first scientific papers, an article on the fatigue of railway axle metals in 1843, led to the development of new construction methods. In 1858, he published his Manual of Applied Mechanics, a work that was of great help to engineers and architects. In 1859 Rankine published his most important work, his Manual of the Steam Engine and Other Prime Movers, a first attempt to conduct a systematic theoretical treatment of the steam engine. Rankine is the creator of the thermodynamic cycle that bears his name being used as a standard for steam facility performance. Rankine has also carried out research in the field of soil mechanics and has published an article on soil retention wall stability called “About the thermodynamic theory of finite longitudinal perturbation waves”. He was also known for the absolute temperature scale that bears his name, Rankine (R), which is closely related to the Fahrenheit grad scale by an additive conversion factor of 459.67.

II. INTRODUCTION

As noted by ANNAN [(1)], William John MacQuorn Rankine was considered a remarkable person, especially for his work on thermodynamics, having developed a complete theory of heat and steam engines. But it was not only his scientific production, for his work is very extensive and could not be completely exposed in this article. After he finished the college in 1838, became assistant to John Benjamin Macneill, supervisor of railroad commission from Ireland. During this work, Rankine developed a technique for constructing railway curves, later known as the Rankine Method. As engineering professor at the University of Glasgow [(1)], he conceptualized potential energy and kinetic energy by studying hydrodynamics. In civil engineering, he developed methods for studying the distribution of forces in building structures, especially in the area of soil mechanics. Rankine pioneered the term energy as synonym for work and created the concepts of potential energy and kinetic energy, and coined the term "adiabatic" that became popular in engineering. He also studied heat theory, a subject of great emphasis in his studies, and the dynamic properties of water vapor. He was one of the first engineers to recognize that train axle fatigue and breakage was caused by the formation and growth of tiny cracks at points of greatest load concentration on the material. Their studies showed the similarity of cases of break pointing to the same cause. In 1858, RANKINE[(3)] wrote the Manual of Applied Mechanics, where he postulated that, in order to guarantee the stability of the masonry arch, it is necessary to avoid any tendency to open the joints, either on the inside or the outside. RANKINE [(4)] in 1857 is a stress field solution that predicts active and passive ground pressure. Rankine's theory forms the basis of a method for determining the pressures on a particular rigid support structure. In 1859 RANKINE[(5)] published the Manual of the Steam Engine and Other Prime Movers, establishing the thermodynamic cycle for power generation based on the use of water as a working fluid. In which he presented a new thermometric scale the absolute zero considered as -459.67F and popularized the concept of energy as the ability to produce work formulated by him in 1853. The main subject of the book is the proposition of the cycle called RANKINE, which was proposed to end the restrictions imposed by the Carnot cycle. Rankine-Hugoniot relations express discontinuity of various quantities through a shock wave or sliding line in a gas. Passing a shock front moving at a velocity Vs, the physical variables ϱ, p and μ change abruptly.

III. BRIEF COMMENTS ON YOUR WORK

As NORTON [2] mentions, Rankine published an article in 1843 entitled The Causes of Unexpected Breakage of Railroad Trunnions, in which it said the material had crystallized and become brittle due to fluctuating tensions. At this time, the problem of locomotive axle fatigue failures became very important with the rapid expansion of the rail system. One of the first articles on fatigue was presented by RANKINE [9] in 1843. He investigated fractured shafts and revealed the destructive effect of stress concentration, showing that the shafts had failed due to the progressive growth of a nucleated brittle crack from a stress concentration source, such as a keyway. The failure due to fatigue is due to a repetition of plastic deformation that occurs in the material in the regions where there is stress accumulation or the propagation of an existing crack left in a manufacturing process. As the fracture propagates in the element, it decreases the section of the part, increasing the stress applied to the remaining section and the crack propagation rate, the material fails when the remaining section is insufficient to resist static loading. The phenomenon of fatigue was first observed around 1800, when the axles of a railway wagon began to fail after a short period in service. Although they were made of ductile steel, they exhibited characteristics of brittle and sudden fractures. The shafts had been designed with all the skill and engineering available at the time, which were based on experiences from studies with statically charged structures. Dynamic loads were therefore a new phenomenon resulting from the introduction of steam powered machines. These axles were fixed to the wheels and rotated together with them.

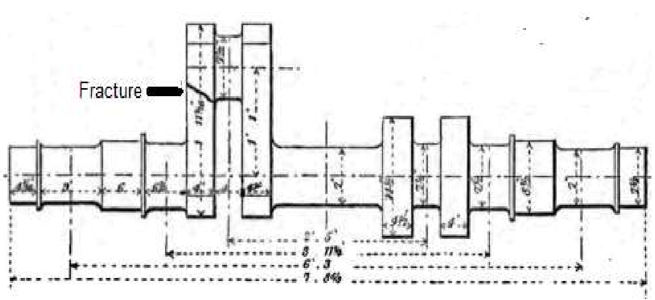


Fig. 1 – Axis of one 19th century locomotive

Source: https://www.maxwell.vrac.puc-rio.br/21361/21361_2.PDF

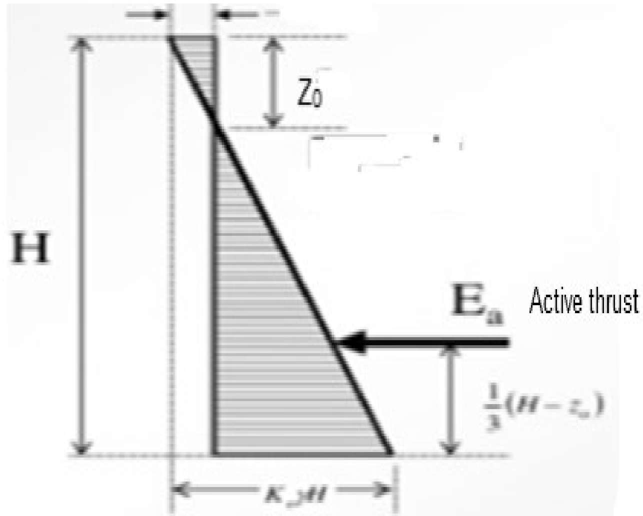
To analyze the stress at the end of a crack, we use a parameter called K, which is the stress intensity factor at the crack end, and is calculated by:

$$K = F\sigma\sqrt{\pi * a}$$

Where a is the crack work, σ is the appalled stress and F is a function that depends on both crack size, crack geometry and the way the load is applied. There is a critical stress intensity value, K_c, for which the material has a brittle fracture from a critical stress σ_c.

$$K_c = F\sigma_c\sqrt{\pi * a}$$

In 1858, RANKINE[3] wrote the Manual of Applied Mechanics, where he postulated that, in order to guarantee the stability of the masonry arch, it is necessary to avoid any tendency to open the joints, either on the inside or the outside. This implies that each thrust center, that is, the point of application of the thrust in the joint plane, must not be further than one-sixth of its thickness from the joint center. In other words, “the stability of an arc is assured if a linear arc, in equilibrium under the same forces acting on the actual arc, can be drawn at the middle third of its thickness. The theory of maximum normal stress theory, developed by RANKINE [4] in 1857, is a stress field solution that predicts active and passive ground pressure. Rankine's theory forms the basis of a method for determining the pressures on a particular rigid support structure when it comes into contact with a mass at a steady state limit. In the study of soil behavior, he proposes a calculation method to size retaining walls, determining the ground impulses. Therefore, Rankine's theory of buoyancy is considered elegant, but in practice it applies very general simplifications. He supposes a granular soil, homogeneous and incompressible in the development of his studies, neglecting the friction between the retaining wall and the soil. It assumes that the ground has no cohesion, the wall has no friction, the wall-ground interface is vertical, the fault surface on which the ground moves is flat and the resulting force is angled parallel to the landfill surface. Rankine's theory assumes that the failure will occur when the maximum principal stress at any point reaches a value equal to the tensile stress in a single sample. Also called the maximum stress theory is satisfactory for brittle materials and not applicable to ductile materials. However, such a proposal does not take into account the effect of the other two main tensions. This theory is used in mining engineering and retains structures widely for testing soil samples before starting a mine. It considers the soil in a state of plastic equilibrium, assumes that the soil is homogeneous, isotropic and has internal friction. The pressure exerted by the ground against the wall is called active pressure. The resistance offered by the ground to an object pushing against it is called passive pressure. Figures 1 and 2 show the action of active and passive thrust and shows the associated formulas.



$$E_a = \frac{K_a \gamma (H - z_o)^2}{2}$$

K is thrust coefficient and γ specific weight of soils.

Fig 2- Representation of active thrust with its formula

Source: ct.ufsm.br/engcivil/images/PDF

K is Thrust coefficient and γ Specific weight from soil

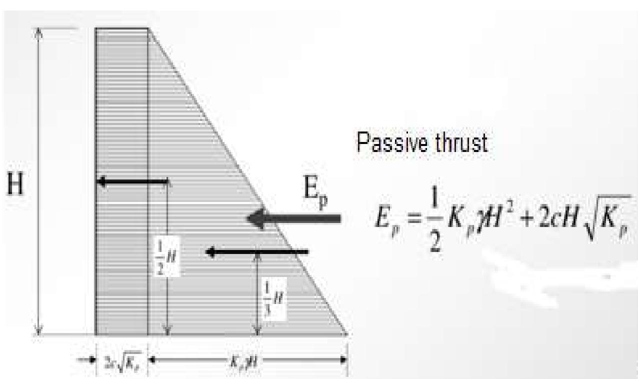


Fig. 3- Representation of passive thrust with its formula

Source: https://edisciplinas.usp.br/pluginfile.php/3399603/mod_resource/content/5/Empuxos.pdf

In 1859 RANKINE[5] published the Manual of the Steam Engine and Other Prime Movers, establishing the thermodynamic cycle for power generation based on the use of water as a working fluid. In which he presented a new thermometric scale the absolute zero considered as -460F and popularized the concept of energy as the ability to produce work formulated by him in 1853. The main subject of the book is the proposition of the so-called RANKINE cycle, which was proposed for end the restrictions imposed by the Carnot cycle. It should be noted that this cycle which is the basis of current steam power generation cycles. It is based on four thermodynamic processes: Process 1-2: Pressurized fluid enters a boiler, where it is heated at constant pressure until it becomes overheated steam. Common sources of heat include coal, natural gas and nuclear power. Process 2-3: Overheated steam expands through a turbine to generate work. Ideally, this expansion is isentropic. With this expansion, both pressure and temperature are reduced. Process 3-4: Steam then enters a condenser, where it is cooled to saturated liquid condition. This liquid then returns to the pump and the cycle repeats itself. Process 4-1: The fluid is ideally pumped in an isentropic form from low to high pressure using a pump. Pumping requires some kind of energy to perform. Figures 4, 5 and 6 show the diagrams for the Rankine cycle.

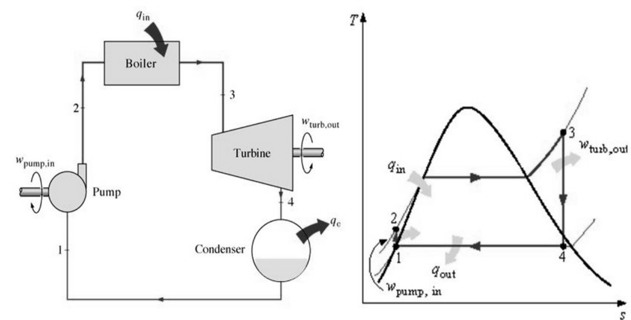


Fig 4 - The simple ideal Rankine cycle

Source : https://br.images.search.yahoo.com/yhs/search

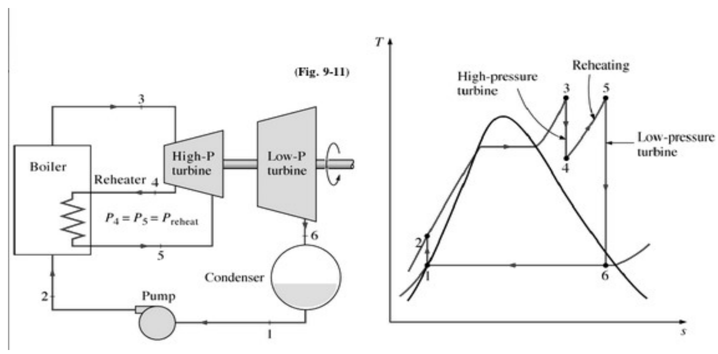


Fig.5- Rankine regenerative cycle

Source: https://qph.fs.quoracdn.net/main-qimg

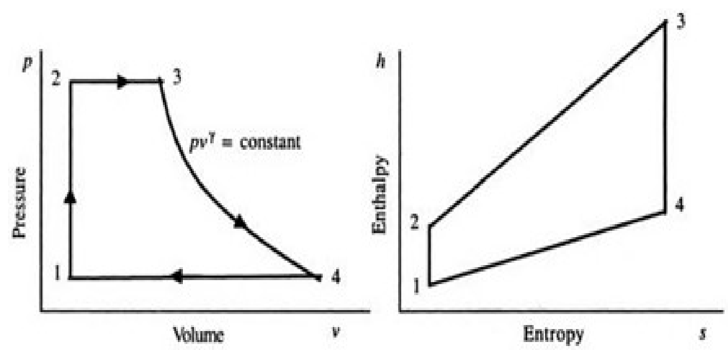


Fig.6- PV and TS diagram of Rankine cycle

Source: https://2.bp.blogspot.com/-P9btCsb3Chk/UdPtmHnKjQI/AAAAAAAAAkY/nPRFYNW4sGs/s533/untitled.bmp

As SHAPIRO [6] indicates, in 1870 William Rankine developed the shockwave theory by clearly presenting the appropriate correlations for continuity, momentum, and energy through a shockwave. In 1887 Pierre Hugoniot, unaware of Rankine's developments published the same correlations, which is why these equations are known as Rankine-Hugoniot Relations. Such relationships express the discontinuity of various quantities through a shockwave or sliding line in a fluid. Passing a shock front moving at a velocity Vs, the physical variables ϱ, p and u change abruptly.

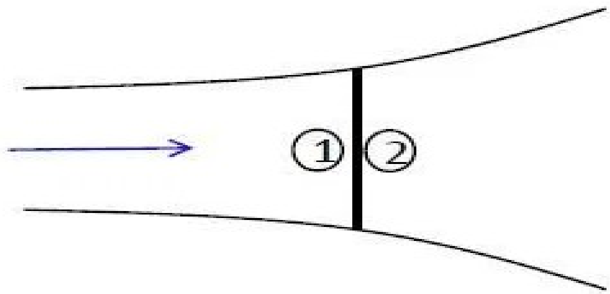


Fig.7Expanding fluid flow into the nozzle

Source : https://jasf1961.files.wordpress.com/2016/06/rankine-hugoniot-relation-summary.jpg?w=9

According to ZIJLEMA [7], the Rankine-Hugoniot equation is an ordinary differential equation in two variables derived from the Euler equations for an inviscid fluid in the case of an orthogonal shockwave to the input stream. Figure 6 shows the expanding flow, which follows the Rankine-Hugoniot relations regarding temperature, pressure, density and velocity of a fluid in shock wave discontinuities. From these equations we can determine the relationships between the parameters immediately before and after shock wave, as shown in figure 8.

Rankine-Hugoniot Equations:	
Temperature	$\frac{T_2}{T_1} = \frac{\left(1+\frac{\gamma-1}{2}M_1^2\right)\left(\frac{2\gamma}{\gamma-1}M_1^2-1\right)}{M_1^2\left(\frac{2\gamma}{\gamma-1}+\frac{\gamma-1}{2}\right)}$
Static Pressure	$\frac{P_2}{P_1} = \frac{2\gamma M_1^2}{\gamma+1} - \frac{\gamma-1}{\gamma+1}$
Density and Velocity	$\frac{\rho_2}{\rho_1} = \frac{v_2}{v_1} = \frac{(\gamma+1)M_1^2}{(\gamma-1)M_1^2+2}$

Fig.8 Equations of Rankine-Hugoniot

Source : https://jasf1961.files.wordpress.com/2016/06/rankine-hugoniot-relation-summary.jpg?w=9

In said equations indices 1 and 2 can be seen in figure (7) showing the nozzle where fluid flows.

IV. RANKINE CYCLE INTERPRETATION

The Rankine cycle is nothing more than a modified form of the Carnot cycle.

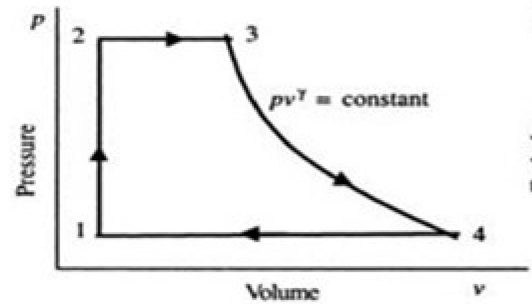


Fig.8- PV diagram of Rankine cycle

Source: https://2.bp.blogspot.com/-P9btCsb3Chk/UdPtmHnKjQI/AAAAAAAAAkY/nPRFYNW4sGs/s533/untitled.bmp

In fact, the Carnot cycle shown in Figure 9 is the father of all thermodynamic cycles because it can provide maximum efficiency for a given working temperature limit.

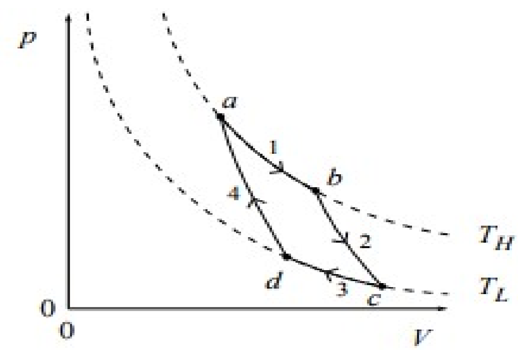


Fig.9 – PV diagram of Carnot cicles

Source : https://pt.wikipedia.org/wiki/Ciclo_de_Carnot

But because Carnot's machine is practically impossible to build, engineers have modified it in different ways so that it can work in real-life situations. But from what has been exposed, it will no longer be a Carnot cycle after modification, it will be a new one. The Rankine cycle is the thermodynamic cycle that most represents the process of energy generation from water vapor. However, other fluids may also be used in special applications such as geothermal generation. The Rankine cycle describes the operation of steam turbines commonly found in power stations. In such stations, work is generated by alternately vaporizing and condensing a working fluid which is normally water but may include other liquids such as ammonia. Work fluid in a Rankine cycle follows a closed cycle, and is constantly reused. The vapor that is observed in power stations comes from the condenser cooling system, not from the working fluid.

V. FINAL CONSIDERATIONS

All civil engineering works rest, in one way or another, on the ground, and many of them, moreover, use the earth as a building element for landfills, dikes, and general landfills; Therefore, its stability and functional and aesthetic behavior will be governed, among other factors, by the behavior of the nesting material located in the depths of influence of the generated stresses or the soil used for model the fillings.

The importance of generating accurate studies for decision making in civil engineering projects is to have an analysis of soils and their behavior. For this, it is necessary to study the mechanics of the soil. Among the basic studies that refer to a civil infrastructure project is ground mechanics. This allows us to determine the geomechanical aspects that occurred throughout the project that we will intervene. Coulomb and Rankine contributed valuable experiences in analyzing ground pressures, allowing the resolution of complex ground pressure problems. With this, we can know and analyze the works that will be projected from simple retaining wall to special retaining structures, using the Rankine and Coulomb models. On the other hand, according to CENGEL (8), there are several known systems currently in use for converting heat into work through a thermodynamic cycle. Among them, the most common is the steam cycle or Rankine cycle. Thermal power cycles are a sequence of thermodynamic processes associated with state changes. In particular, power cycles are used to convert thermal energy into work, usually employing gases and water as fluids, in the latter case the cycles are called steam cycles, or Rankine cycle. This type of power system allows you to convert energy from low-cost fuels into electricity. Much of the electricity produced worldwide uses this technology. The Rankine cycle is widely used in power plants today and will certainly continue to be in the future.

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