A point of view on Otto cycle approach specific for an undergraduate thermodynamics course in CMU

F Memet\textsuperscript{1} and A Preda\textsuperscript{1}
\textsuperscript{1}Constanta Maritime University, Faculty of Naval Electro-Mechanics, 104 Mircea cel Batran Street, 900663, Constanta, Romania
E-mail: feizamemet@yahoo.com

Abstract. This paper refers to the description of the way in which can be presented to future marine engineers the analysis of the performance of an Otto cycle, in a manner which is beyond the classic approach of the course of thermodynamics in Constanta Maritime University. The conventional course of thermodynamics is dealing with the topic of performance analysis of the cycle of the internal combustion engine with isochoric combustion for the situation in which the working medium is treated as such a perfect gas. This type of approach is viable only when are considered relatively small temperature differences. But this is the situation when specific heats are seen as constant. Instead, the practical experience has shown that small temperature differences are not viable, resulting the need for variable specific heat evaluation. The presentation below is available for the adiabatic exponent written as a linear function depending on temperature. In the section of this paper dedicated to methods and materials, the situation in which the specific heat is taken as constant is not neglected, additionally being given the algorithm for variable specific heat. For the both cases it is given the way in which it is assessed the work output. The calculus is based on the cycle shown in temperature-entropy diagram, in which are also indicated the irreversible adiabatic compression and expansion. The experience achieved after understanding this theory will allow to future professionals to deal successfully with the design practice of internal combustion engines.

1. Introduction
Maritime Education and Training is the path towards a successful career in shipping industry, which despite of the present global economic crises, is asking for highly qualified marine engineers in the context of the world’s fleet growth [1].

Developments in marine engineering, found in new and future ships, offer major benefits in terms of fuel consumption, maintenance, carrying capacity, environmental behavior, etc. All these aspects must be reflected in the education and training of future marine engineers [2].

In Constanta Maritime University (CMU), an important educational outcome of its engineering programme is the capacity of graduates to design a component or a system. Taking into account that population of the world is increasing and the natural resources are depleting, future marine engineers will face the energy efficiency challenge. In this context, future graduates will deal with the problem related to the increase of the efficiency of power systems.

Thermodynamics is an important component of mechanical engineering curricula, as well as of marine engineering curricula. In Constanta Maritime University, future marine engineers, encounter the Otto cycle during Thermodynamics 1 course, delivered in their second year of study. Because
large temperature differences exist in the practical cycles, the constant specific heat assumption is not valid, therefore this topic should be extended when it is delivered to students. The efficiency evaluation of the cycle of the internal combustion engine with isochoric combustion, considering the heat transfer and also constant and not constant specific heats of the gas, by the involvement of the finite-time thermodynamics, leads to a better understanding of the modern aspect of this discipline.

The aim of these algorithms presented below is to provide to future marine engineers guidance for the design of practical Otto engines, by choosing the optimal situation for the desired use.

2. Methods and Materials

The air standard Otto cycle is shown on temperature–entropy coordinates in figure 1. The closed thermodynamic cycle 1-2t-3-4t consists of four internally reversible processes: reversible adiabatic compression (1-2t), constant volume heat addition (2t-3), reversible adiabatic expansion (3-4t) and constant volume heat rejection (4t-1). In the mentioned figure, it is possible to be seen the processes 1-2 and 3-4t, which are the irreversible adiabatic processes – in which internal irreversibility in the real compression and expansion processes are considered.

![Figure 1. (T-s) diagram for the air standard Otto cycle.](image)

The Otto cycle analysis, which is developed on the assumption that the working fluid behaves as an ideal gas with constant specific heat, is viable for relatively small temperature differences; but in the practice of thermal machines, the temperature differences are important, making useful the examination of the variable specific heat case [3].

In this study, dealing with the performance of the irreversible Otto cycle, it will be used Finite Time Thermodynamics, which is a tool able to reveal the optimal time path of any cyclic process with friction and heat leakage and to offer a clear image of how irreversibility influences the performance of thermal processes [4].

The performance of the analysed air standard Otto cycle is evaluated with:

\[
\eta = \frac{W_{out}}{Q_{in}}
\]

meaning the ratio between the work output and the heat added to the working fluid.

2.1. Constant specific heat case

When working with an ideal gas for which are known its initial conditions, the maximum temperature and minimum volume, it is easy to find the other states, the heat input, heat rejected and the work output in the analyzed cycle, by the use of ideal gas laws and the first principle of thermodynamics [5].
For the isentropic compression process \((1-2t)\) and isentropic expansion process \((3-4t)\) are written the following equations:

\[
\frac{T_{2t}}{T_1} = r^{k-1}
\]

\[
\frac{T_{3t}}{T_3} = r^{k-1}
\]

where:
- \(r\) – the compression ratio for the engine \((r = V_1/V_2)\),
- \(V_1\) – the total volume of the cylinder,
- \(V_2\) – cylinder clearance volume,
- \(k\) – ratio of the specific heats \((k = c_p/c_v)\).

The investigation is focused on reversible and irreversible processes, thus it is requested the definition of the compression and expansion efficiencies, which describe the internal irreversibilities of the adiabatic processes [6]):

\[
\eta_c = \frac{T_{2t} - T_1}{T_2 - T_1}
\]  
(4)

\[
\eta_e = \frac{T_{3t} - T_1}{T_2 - T_1}
\]  
(5)

The total energy of the fuel \((Q_{fuel})\), the heat added to the working fluid \((Q_{in})\), the heat leakage \((Q_{ht})\) and the work output \((W_{out})\) are evaluated with [7]:

\[
Q_{fuel} = \eta_{com} m_f Q_{LHV}
\]  
(6)

\[
Q_{in} = Q_{fuel} - Q_{ht}
\]  
(7)

\[
Q_{ht} = m_t B(T_2 + T_3)
\]  
(8)

where:
- \(m_t\) – fuel amount,
- \(m_f\) – air-fuel amount inducted into the cycle,
- \(\eta_{com}\) – combustion efficiency,
- \(B\) – constant,
- \(Q_{LHV}\) – the lower heating value of the fuel.

\[
m_f = m_f \left[ 1 + \frac{1}{(m_{air}/m_f) \Phi} \right]
\]  
(9)

Above, \(\Phi\) is the equivalence ratio and “s” refers to stoichiometric conditions.
\[ Q_{in} = \frac{R_{air} m_t}{k-1} (T_3 - T_2) \]  

\[ W_{out} = \frac{R_{air} m_t}{k-1} (T_1 - T_2 + T_3 - T_4) \]

where \( R_{air} \) – characteristic gas constant of air.

2.2. Variable specific heat case

Having in view the existence of large temperature difference in the practical cycles, the specific heat with constant pressure and the specific heat with constant volume depend on temperature, resulting that the adiabatic exponent “\( k \)”, depends on temperature also.

A reversible adiabatic process, between states \( i \) and \( j \), for which \( k \) is variable, can be divided into infinitesimally small processes, each of them with constant \( k \). For any of these processes, when occur infinitesimally small changes in temperature \( (dT) \) and in volume \( (dV) \) of the working fluid, the equation for reversible adiabatic process with variable \( k \) is written as [8]:

\[ TV^{k-1} = (T + dT)(V + dV)^{k-1} \]

According to Ebrahimi [9]:

\[ k = k_0 - k_1 T \]

Above, \( T \) is absolute temperature and \( k_0, k_1 \) are constants. In this respect, from equation (12) results:

\[ Q_{in} = m_t \int_{T_i}^{T_f} c_v \, dT = m_t \int_{T_i}^{T_f} \left( \frac{R_{air}}{k_0 - k_1 T - 1} \right) \, dT = \frac{m_{air} R_{air}}{k_1} \left[ 1 + \frac{\Theta}{(m_{air}/m_f)} \right] \ln \left( \frac{k_0 - k_1 T_2 - 1}{k_0 - k_1 T_3 - 1} \right) \]

\[ Q_{out} = m_t \int_{T_1}^{T_2} c_v \, dT = m_t \int_{T_1}^{T_2} \left( \frac{R_{air}}{k_0 - k_1 T - 1} \right) \, dT = \frac{m_{air} R_{air}}{k_1} \left[ 1 + \frac{\Theta}{(m_{air}/m_f)} \right] \ln \left( \frac{k_0 - k_1 T_1 - 1}{k_0 - k_1 T_4 - 1} \right) \]

\[ W_{out} = \frac{m_{air} R_{air}}{k_1} \left[ 1 + \frac{\Theta}{(m_{air}/m_f)} \right] \ln \frac{(k_0 - k_1 T_2 - 1)(k_0 - k_1 T_4 - 1)}{(k_0 - k_1 T_3 - 1)(k_0 - k_1 T_1 - 1)} \]

3. Results and discussion

An assessment aiming the performance evaluation of the Otto cycle in the case in which internal irreversibility in the real compression and expansion processes are considered was described in terms of thermal efficiency.

In the presented calculation procedure was considered the case of constant specific heats, which is a theoretical situation and also the case of variable specific heats, which corresponds with reality since in practice temperature differences are important.

For both presented cases are given formulas leading to the calculation of the thermal efficiency of the cycle of the internal combustion engine with isochoric combustion (Otto).

The irreversibility of the two adiabatic processes of the cycle was not ignored and were given formulas of the specific efficiencies. For the first case in discussion, \( T_2 \) can be found if are known \( r, \eta_c, \eta_E \) and \( T_1 \) by the use of relation (2). By introducing \( T_2 \) in equation (4), results \( T_2 \). The temperature at the end of combustion is calculated by replacing equation (7) in equation (10).
results from equation (3); when it is introduced in equation (5), it is possible to get $T_4$. With $T_1$, $T_2$, $T_3$ and $T_4$ evaluated, are used equations (11) and finally (1), to have a theoretical basis of the cycle performance analysis.

For the second case in discussion, $T_{2t}$ can be calculated if known $r$, $\eta_c$, $\eta_E$ and $T_1$ are from equation (14). Then, $T_{2t}$ is introduced in equation (4), to be found $T_2$.

The temperature at the end of the combustion is calculated using relations number (7) and (15), while the temperature and the end of the theoretical expansion results from formula (14). When it is introduced in equation (5), it is possible to get temperature at the end of real expansion. Being known temperatures in the characteristic points of the actual cycle, by using equations (17) and (1), it is possible to complete the proposed assessment.

4. Conclusions
An efficient marine engineering program, such is the one developed in CMU, provides to future marine engineers the ability to deal with engineering design. The short review of the standard cycle specific to the internal combustion engine with isochoric combustion (Otto), is the foundation of the theoretical exposure in discussion.

In the context of new technologies penetration in the maritime sector and of the need for highly qualified marine engineers, thermodynamics course in CMU was updated. Such an aspect is demonstrated through this article. The classical approach related to the performance of Otto cycles was based on the influence of the constant specific heat. This situation is available only when considering small temperature differences; in practice, because of the large temperature differences, the above mentioned should be reconsidered.

As a result, when delivered to the students, this topic was extended to the analysis of the effect of the specific heats depending on temperature on the efficiency of the irreversible cycle of the internal combustion engine with isochoric combustion, in order to offer to future professionals a tool for optimal design and working conditions assessment specific to above mentioned cycles.

References
[1] Baylon A M, Ma V E and Santos R 2011 The challenges in Philippine Maritime Education and Training International Journal of Innovative Interdisciplinary Research 1 pp 34-43
[2] Saharuddin A H, Sulaiman O O, Kader A S A and Wan Nick W B 2011 Marine Engineering as future career in Malaysia Business Management Dynamics 1(2) pp 01-10
[3] Anwar Beg O, Rashidi M M and Mehr N F 2014 Comparative thermodynamic study of air standard cycles with heat transfer and variable specific heats of the working fluid Int. J. Appl. Math. and Mech. 10(2) pp 41-60
[4] Mehta H B and Bharti O S 2009 Performance analysis of an irreversible Otto cycle using Finite Time Thermodynamics Proc. of the World Congress on Engineering II p 5
[5] Huleihil M and Mazor G 2012 Irreversible performance characteristics of air standard Otto cycle with polytropic processes Applied Mechanical Engineering 1(3) p 6
[6] Ust Y, Sahin B and Safa A 2011 The effects of cycle temperature and cycle pressure ratios on the performance of an irreversible Otto cycle Acta Physica Polonica A 120 pp 412-416
[7] Ebrahimi R 2010 Theoretical study of combustion efficiency in an Otto engine Journal of American Science 6(2) pp 113-116