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Conceptual issues related to reversibility and reversible work produced in closed and open flow systems

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ABSTRACT

The concepts of reversibility and reversible work are subtle and illusive. Students often face difficulties in understanding these concepts. The definitions of reversibility given in textbooks on thermodynamics are generally descriptive and qualitative, subject to interpretation. The reversible work often discussed in the textbooks is actually the work produced in a mechanically reversible process and not the work produced in a completely reversible process. Although the $P-V$ work produced in a mechanically reversible process is a path-dependent quantity, the work produced in a completely reversible process (closed or open system) is not a path-dependent quantity. It is a state function provided that the system interacts with a single thermal energy reservoir. In this article, the precise definitions of reversibility which are unambiguous and quantitative are discussed. The work produced in a reversible process is analyzed and discussed in detail. Both closed and open systems are considered. The material described in this article is suitable for third year chemical engineering students who have completed an introductory engineering thermodynamics course in their second year.

1. Introduction

Thermodynamics is a branch of engineering sciences that deals with all types of energy – renewable and non-renewable – in terms of availability (exergy), conversion, efficiency, and destruction of availability (Dukhan and Schumack, 2013). Engineers use the principles of thermodynamics in the analysis and design of a wide variety of energy systems including power plants, automobiles, air conditioning systems, refrigeration systems, rockets and jet engines (Mulop et al., 2012). Thermodynamics also plays an important role in the analysis and design of chemical reactors, compressors, pumps, absorption columns, distillation columns, and other process equipment. A thorough understanding of thermodynamics is indispensable for the graduating engineers in order to address the global issues related to energy crisis and global warming. Due to its immense practical importance, thermodynamics is an essential part of the global engineering curricula (Mat and Hassan, 2005; Abu-Mualweh, 2004; Mulop et al., 2012).

Thermodynamics is considered to be one of the most difficult and abstract disciplines of the physical sciences (Fuchs, 1987). It is appropriate to quote Arnold Sommerfeld (well-known German theoretical physicist) here (Dahm and Visco, 2015):

> "Thermodynamics is a funny subject. The first time you go through it, you don't understand it at all. The second time you go through it, you think you understand it, except for one or two small points. The third time you go through it, you know you don't understand it, but by that time you are so used to it, so it doesn't bother you any more"

Engineering students all over the world face difficulties in learning thermodynamics. This is a well-documented fact in the literature (Mulop et al., 2012; Dukhan and Schumack, 2013; Hassan and Mat, 2005; Abu-Mualweh, 2004; Patron, 1997; Junglas, 2006; Meltzer, 2004; Anderson et al., 2005; Cotignola et al., 2002; Liu, 2011; Bullen and Russel, 2007; Baher, 1998;

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Nomenclature

C_V	Heat capacity at constant volume
H	Enthalpy
P	Pressure
Q	Heat
R	Universal gas constant
S	Entropy
T	Temperature
U	Internal energy
V	Volume
W	Work

Greek symbols

γ	Heat capacity ratio ($=C_P/C_V$)
ψ	Exergy

Table 1 – National average scores in the morning thermodynamics section of the fundamental engineering exam (Dukhan and Schumack, 2013).

Year	Civil	Mechanical	Electrical
2002	43%	63%	44%
2003	44%	N/A	N/A
2004	29%	57%	N/A
2005	44%	57%	N/A
2006	48%	62%	47%
2007	51%	63%	N/A
2008	49%	61%	50%
2009	53%	71%	N/A
2010	32%	45%	N/A
2011	42%	56%	43%
2012	58%	70%	61%

Kelly, 2002; Huang and Gramoll, 2004; Cox et al., 2003; Forbus et al., 1999; Chaturvedi et al., 2007; Colbourn and Lindauer, 1994; Meltzer, 2006; Grigull, 1990; Fuchs, 1987). The national passing rates in thermodynamics are generally low as indicated by a recent survey of the National Council of Examiners for Engineering and Surveying (Dukhan and Schumack, 2013). Table 1 presents the national average scores in the morning thermodynamics section of the fundamental engineering exam. The scores range anywhere from 29 to 71%. The mechanical engineering students happen to score the highest and the civil engineering students score the lowest in this survey.

Some researchers have described thermodynamics as the gateway course (Manteufel, 1999) in engineering in the sense that a good correlation exists between the student performance in thermodynamics and other courses in the curriculum.

Extensive research has been carried out on the effectiveness of different pedagogical approaches to enhance the teaching and learning of thermodynamics (Mulop et al., 2012). Among the various approaches used are: traditional lecture style approach, active learning techniques, computer-based instruction, virtual lab—a web-based student learning tool for thermodynamic concepts, interactive multimedia e-book, and blended learning approach. Each approach has its own pros and cons.

1.1. *Objectives of this work*

The first course in thermodynamics taught in most undergraduate engineering programs is almost entirely restricted to *equilibrium* thermodynamics. The key assumption of equilibrium thermodynamics is *reversibility* and yet the students rarely understand the concepts of *reversibility* and *reversible work* well enough in their first course.

The main objective of this article is to clarify the concepts of reversibility and reversible work. These concepts are explained through examples. Practice problems are included to assist the students in understanding these fundamental concepts.

2. Reversibility—a threshold concept

Reversibility is a threshold concept as defined by Meyer and Land (2003). It is a gateway to the entire field of equilibrium thermodynamics. The analysis and solution of problems within the framework of equilibrium thermodynamics are based on the assumption of reversibility. Therefore, a good understanding of the threshold concept of reversibility is necessary for a learner to make progress in the field of equilibrium thermodynamics and to solve problems of practical interest within the framework of equilibrium thermodynamics.

2.1. *Overview of different definitions of reversibility*

Some of the difficulties that the students face in grasping the concept of reversibility can be attributed to the numerous definitions of reversibility given in various thermodynamics textbooks. Here are some sample definitions of reversibility presented in the thermodynamics textbooks (Dahm and Visco, 2015; Smith et al., 2005; Tester and Modell, 1997; Koretsky, 2004; Castellan, 1983; Kyle, 1999; Sandler, 1999; Elliot and Lira, 1999; Levine, 2002; Potter and Somerton, 2006):

> "A process is reversible when its direction can be reversed at any point by an infinitesimal change in external conditions"

> "A process will be called reversible if a second process could be performed in at least one way so that the system and all elements of its environment can be restored to their respective initial states, except for differential changes of second order"

> "A process is reversible if, after the process occurs, the system can be returned to its original state without any net effect on the surroundings. This result occurs only when the driving force is infinitesimally small"

> "Suppose that a system undergoes a change in state through a specified sequence of intermediate states and then is restored to its original state by traversing the same sequence of states in reverse order. Then if the surroundings are also restored to their original state, the transformation in either direction is reversible"

> "A process that moves a system from state A to state B is said to be reversible if the work and heat effects realized from the process are sufficient to restore the system to its original state (state A). Actually, we are considering a cycle $A \rightarrow B \rightarrow A$ consisting of two reversible steps which when completed leaves no changes in either the system or surroundings"