AC 2009-1620: ENTHALPY IN A BOX: TEACHING OPEN VS. CLOSED SYSTEM WORK TERMS

Andrew Foley, United States Coast Guard Academy

Michael Plumley, United States Coast Guard Academy

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Teaching open v closed system work terms.

Abstract

In teaching a general approach to thermodynamics the authors have reduced the equation count in their course to basically one accounting equation, the Reynolds Transport equation. While this has been well received by students it does require that they, in turn, have a greater physical understanding of problems as success is now examined by their skill in application and manipulation of the fundamental equation rather than in successful recall from a large list of problem specific equations.

This paper focuses on one area that continually causes problems, specifically the calculation of work done by open and closed systems. Some novel physical explanations are described which have proven successful in eliminating this area of confusion. The paper finishes with a somewhat controversial proposal that 'flow work' be taken out of the convected energy terms and instead form part of the net work terms. The benefits of just having internal energy as opposed to internal energy and enthalpy considerations are highlighted.

Introduction

Enthalpy, somewhat like entropy appears to be one of thermodynamic's mysterious and abstract properties due primarily to difficulty in physical comprehension. Unlike entropy however, one could argue that enthalpy does not bring as much to the table. After all, it is defined, somewhat arbitrarily, from properties that students generally already have a good physical handle on. i.e. Pressure, volume and internal energy. This is particularly true at the author's institution were a reasonable investment of time is spent on deriving the gas equation for state by using particle dynamics to really 'knock home' the link between, temperature, internal energy, pressure, mass and volume. So the question is begged, why bring in a new property that is not required?

It is also somewhat surprising to see how vaguely and randomly enthalpy is introduced in many engineering texts, many justifying its introduction simply by saying 'because the sum U+pV occurs so frequently …. It is convenient to give the combination a name, enthalpy"[1] Some texts allude to it is an energy property that includes 'flow work', and this in turn is somewhat diversely defined. Indeed the root of the problem could be traced back to the Greek origins of the word itself, 'enthalpos' [2], translated to 'to put heat into'. Again as most undergraduates will recite, enthalpy is a property and heat is not, so immediately we are running into problems here. Another early discussion by Planck [3] does attempt to be more precise by referring to Gibb's description of a property, H called 'the heat function at constant pressure', while more precise this is a bit of a mouthful and again relates to a specific application of enthalpy due to the 'heat of reaction'. In contrast, and as can be seen in this paper we can use the property of enthalpy with no particular reference to heat transfer.

Particle dynamics and the derivation of the equation of state for a monotomic gas

This may seem a strange starting place for a paper that purports to focus on enthalpy but the importance of the gas equation of state cannot be under emphasized. A very real image problem that thermodynamics suffers from is an abundance of, what appears for undergraduates to be, untenable properties with strange names. By using the analogy of billiard balls randomly crashing around a room and throwing in some Newton's second law and assorted high school physics, it is possible to achieve a multitude of goals.

First the association of temperature, internal energy and the particles velocity for a monatomic gas is established:-

$$U = m.CvT = \tfrac{1}{2}.m.3.V_x^{\,2} \qquad (1)$$

Thermal internal energy is equal to the kinetic energy for a monatomic gas with only 3 degrees of freedom. The particles are then considered colliding with the wall and having their momentum changed by virtue of their direction of motion being reversed normal to the wall and this is then used to derive the force on a wall and hence the pressure:-

$$P = \frac{m.V_x^{\,2}}{V_{ol}} \qquad (2)$$

Finally, combining (1) and (2), pressure and temperature are related by :-

$$P.V_{ol} = m.\tfrac{2}{3}Cv.T = m.R.T \qquad (3)$$

the gas equation of state for a monatomic gas.

The end result of this excursion, apart from the derivation of gas equation of state, is that a physical interpretation and analytical link between the important properties of Pressure, Temperature and internal energy is formed. The importance of this understanding is seen later in the course when students incorporate these properties into the various guises of the Reynolds Transport equation with relative ease. Enthalpy however does not fall into this category however.

Reynolds Transport Equation

Foley [4] discusses the central importance of the Reynolds Transport equation to all the primary tools used in an undergraduate thermodynamics course.

$$\dot{B}_{in} - \dot{B}_{out} + (\dot{m}b)_{in} - (\dot{m}b)_{out} + \dot{B}_{gen} = \dot{B}_{CV} \qquad (4)$$

Where B is any property of interest. The key concept here is that this is simply an accounting equation and as long as the property B and the specific property b are the same thing all is well. (i.e. Don't mix your apples and oranges !)

The reason this is stressed here is that the appearance of enthalpy in the energy equation appears on first glance to contradict this. i.e. Should not the mass convect in specific internal energy into the control volume rather than specific enthalpy ?

Enthalpy in the box

When considering closed systems, issues of enthalpy do not arise and as such when students progress to open systems the need for this new property appears even more suspect. To justify its existence the following example is used by the author :-
Considering the open system shown in Figure 1, below :-

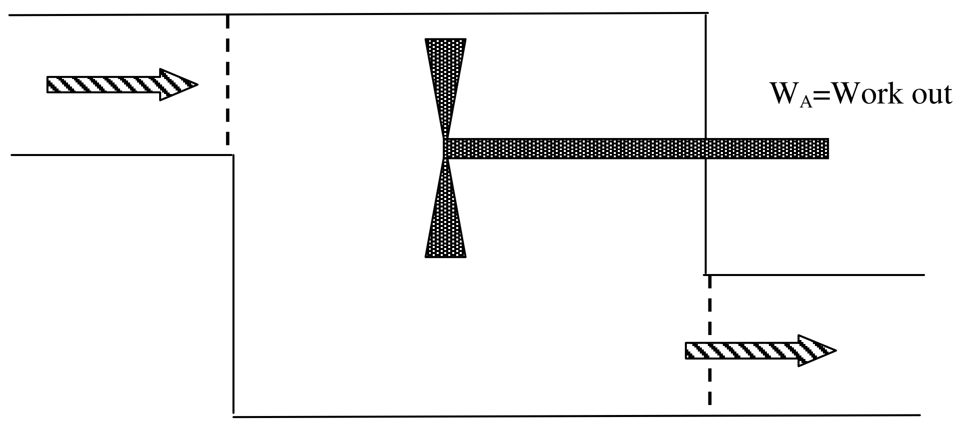


Figure 1. General open system control volume

With a little imagination one could see that for a small time δt the above system could be modeled as three separate control volumes as shown below (Figure 2.) :-

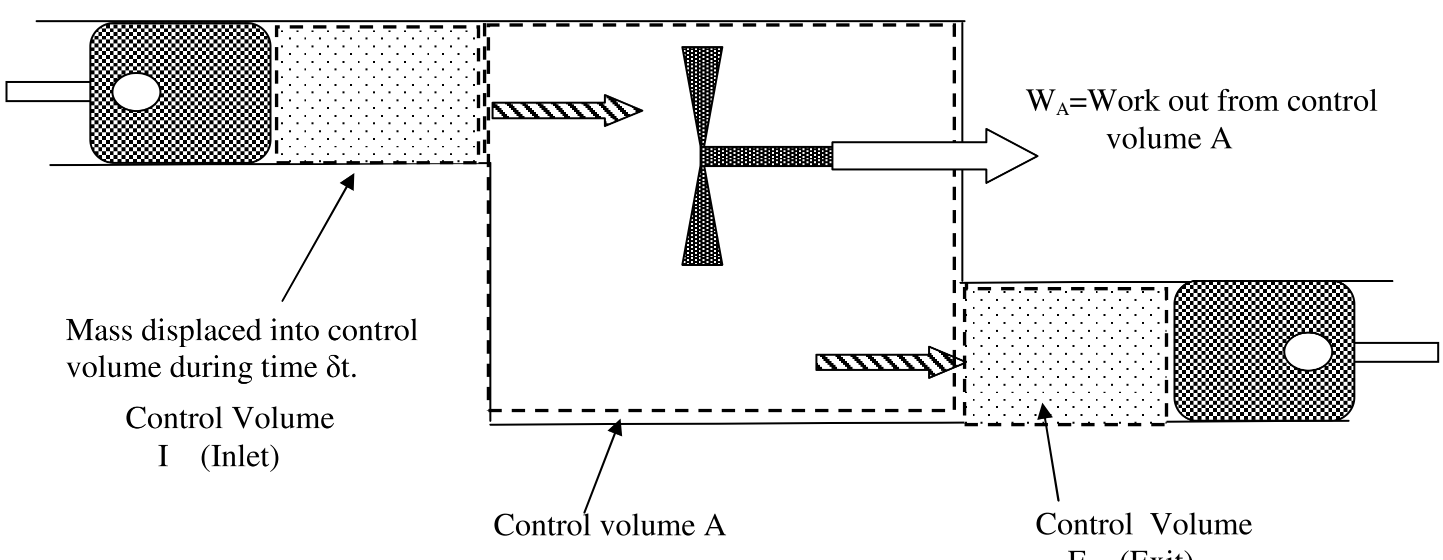


Figure 2. Open system 3 control volume model.

Considering control volume (I), inlet only, (piston shown to illustrate how the mass is pushed into control volume A, the Reynolds transport energy equation in a finite time version becomes :-

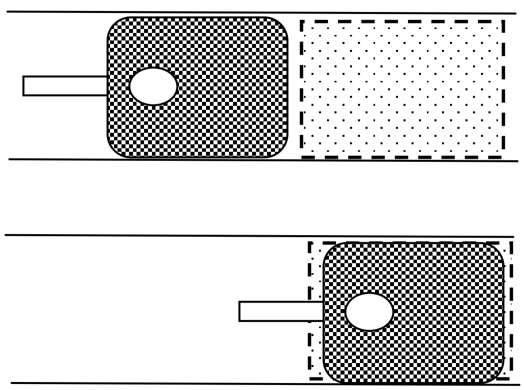
$$DU_I = \partial U_I + \sum Q_I - \sum W_I + \sum (me)_I \qquad (5)$$

Where ∂U_I is internal energy generation and the little e term is as yet undefined, its some measure of energy consistent with internal energy. First instincts are, perhaps, that it should indeed be internal energy.

For the purposes of brevity we will assume there is no internal energy generation and no heat transfer in the inlet control volume, and hence this reduces to :-

$$DU_I = W_I + me_I \qquad (6)$$

Considering the change in internal energy of the inlet control volume further, it is the difference between its initial energy and its final energy, i.e. Figure 3.



Internal energy $= m_I.Cv.T_I$

Internal energy = 0 (No mass left.)

Figure 3. General inlet control volume

Therefore equation simplifies to :-

$$m_I.Cv.T_I = W_I + me_I \qquad (7)$$

Now the work done on the piston by forcing the air into control volume A is given by :-

$$W_I = \int_{vI}^{0} p.\partial v = -p_I.V_I \qquad (8)$$

Assuming the pressure of the air remains constant on the inlet supply.
(Note also that the work done by the inlet control volume is negative as the work is done on the control volume.)

Returning to our first law for the inlet control volume it can therefore be shown that our new e term is :-

$$e_I = \frac{m.Cv.T_I + p_I.V_I}{m} = Cv.T_I + p_I.v_I = u_I + p_I.v_I \qquad (9)$$

In summary the energy being convected out of the inlet control volume comprises the internal energy of the mass and the work done in pushing that mass into control volume A. Interestingly it is completely uninfluenced by the conditions in control volume A.

Similarly for the exit control volume E,

$$e_E = \frac{m.Cv.T_E + p_E.V_E}{m} = Cv.T_E + p_E.v_E = u_E + p_E.v_E \qquad (10)$$

Returning now to our control volume A,

$$DU_A = \sum Q_A - \sum W_A + m_I.(u_I + p_I.v_I) - m_E.(u_E + p_E.v_E) \qquad (11)$$

Again it is interesting to note that the convected terms comprise properties that are completely defined outside of the control volume A which we are ultimately analyzing.
At this point convention is that there is 'convenience' to be had by grouping the terms in the brackets into one term. i.e. the property enthalpy (h) is justified.
Hence,

$$DU_A = \sum Q_A - \sum W_A + m_I.(h_I) - m_E.(h_E) \qquad (12)$$

This convenience however comes at a price. First, internal energy is a property that was closely related to pressure and temperature and fundamental in our earlier derivation of the gas equation of state, enthalpy has no similar physical comprehension. Secondly, and again as previously discussed, the real power of the Reynolds Transport equation is its presentation as a simple accounting equation. As any accountant knows you cannot simply add different currencies without making appropriate conversions. Yet here we are convecting specific enthalpy into a control volume to find a change in internal energy without any apparent conversions. With the time and rigor invested in teaching these earlier concepts this is a steep price for 'convenience'. Although this may all seem a little subtle, it is a major cause of confusion and frustration amongst students.

An option, somewhat radical perhaps, could therefore be to return to equation (4) and take the 'boundary work' terms (p.v) and transfer them into the work summation term, or better still, there own boundary work summation term.

i.e.

$$DU_A = \sum Q_A - \sum W_A + \sum W_{A\_Boundary} + m_I.(u_I) - m_E.(u_E) \quad (13)$$

Where $\sum W_{A\_Boundary} = m_I.(.p_I.v_I) - m_E.(p_E.v_E)$ (14)

The benefit of this latter method is that we will end up with a Reynolds transport energy equation that is consistent with derivations where the properties of mass, momentum, entropy etc are considered. The appearance of yet another mysterious property has also been avoided.

A final differential form of this alternative equation could be as follows :-

$$\frac{DU_{CV}}{Dt} = \frac{\partial U_I}{\partial t} + \sum \dot{Q}_{net\_in} - \left[\sum \dot{W}_{net\_out} + \sum \dot{W}_{Boundary}\right] + \sum (\dot{m}u)_{net\_in} \quad (15)$$

Conclusion

Consistency in teaching thermodynamics is a great ally in keeping students confidence. Similarly a physical sense of what properties are also helps tremendously. It has been this author's philosophy to establish a solid link between the primary physical properties of temperature, pressure and internal energy, through a particle dynamics derivation of the gas equation of state. Accounting for the assorted properties of interest in any Thermodynamic process or cycle has then been undertaken using almost exclusively one form or another of the Reynolds Transport equation. Conservation of mass, energy, entropy and momentum equations have all been done in the same manner and this has been consistently well received by students.

The introduction of enthalpy as a mere 'convenience' however does not assist in this teaching methodology and if anything has caused confusion. A simple control volume approach detailed in this paper has shown how enthalpy arises and the paper goes further to show how it could be removed and an energy formulation arrived at where enthalpy is not required. Instead an equation with a consistent property and conventional work and heat transfer terms would result.

Despite the apparent benefits of such a formulation, the author is realistic and recognizes that enthalpy is not likely to disappear any time soon. Like the first and second law it has been around so long it has attained its tenure.

References

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[3] Planck M. (1917). Thermodynamics 3rd revised Ed. Dover Publications , inc.

[4] Foley.A (206) . Applying the 'catch all' general control volume and the Reynolds Transport Equation to improve Thermodynamics instruction. ASEE National Convention, Chicago. 2006. Paper no. AC-2006-862