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The Engineering Theory and Application of Air Sparge and Soil Vapor Extraction

A Treatise in Distributed Compressible Fluid Transport using Horizontal Wells

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PART 1

I. Abstract

Air Sparge (AS) and Soil Vapor Extraction (SVE) technologies have been in use for several decades to effect environmental remediation at a multitude of sites. It may be qualitatively argued that the majority of delivery and removal mechanisms for such technologies have been via the use of traditionally installed vertical wells. For somewhat lesser a period of time, directionally drilled (horizontal) wells have been used in the environmental industry. Increasingly, a greater number of installations have seen the merger of AS and SVE technologies with horizontal wells being used as the technology "delivery system". In these growing number of installations, it has been the prevailing experience of the author that such AS/SVE-horizontal well hybrid treatment systems either partially or completely fail to achieve their objective goals *as designed*, and fail to effect remediation to the degree and extent desired. A preponderance of observation and analysis of such systems has led to the conclusion that these failures are not due to either the misapplication of AS/SVE technologies or horizontal wells, but rather to the lack of technical understanding and proper *application* of the Laws of Physics to correctly design these systems such that they *can work*. The purpose of this treatise is to explore the Laws of Newtonian Physics, specifically those of Thermodynamics and Fluid Dynamics so as to provide an overview of the operation of horizontal well systems in baseline and alternative conditions. These ensuing examples are presented to illustrate the complex operating nature of such systems and assist the reader in better understanding and appreciating the *necessary complexities* involved in designing such systems. Only by considering such complexities through rigorous engineering analysis and design effort can hybrid AS/SVE-horizontal well treatment systems function *as designed* and *as desired*.

II. Background

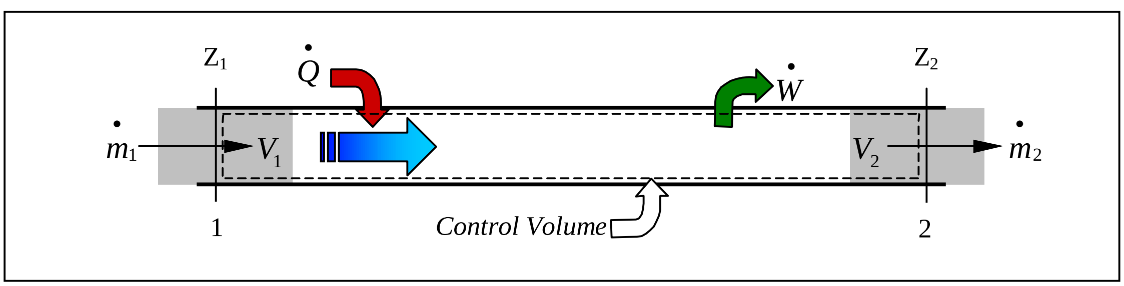
The world about us, and everything we do or are a part of, is governed by the Laws of Newtonian Physics. Regardless of what we are doing or attempting to accomplish by the conveyance of objects or substances, the physical laws applicable to the process involved, in consideration of the conditions at hand <u>always</u> apply. Whether we are standing still in our homes, driving our car, flying in a plane or taking a dip in the ocean, these laws <u>always</u> apply <u>without exception</u>. Further, these laws apply to <u>all</u> other objects and substances, be they solid, liquid, gas or plasma and they apply about *and within* all objects and substances.

In this regard, the laws of physics and their base descriptive equations that apply to the transport of compressed air in a pharmaceutical pill-transport system *are the same as* that for <u>all</u> AS and SVE systems, <u>all</u> horizontal and vertical wells and the dispersion of air or vapor to and from these wells in <u>all</u> soils. From the laws-of-physics perspective and that of the fluid being transported, the differences in these systems are completely irrelevant.

By Newtonian Physics principles given any *control volume* (which will be described shortly) <u>all</u> the mass <u>and</u> energy *entering* a system <u>must</u> *exit* the system. The basic descriptive equation for all steady state steady flow processes, such as would be the case for all AS/SVE systems, is a thermodynamic one. This equation, commonly referred to as the *Steady State Thermodynamic Energy Equation* is as follows:

$$\dot{Q} + \sum \dot{m}_1 \left(h_1 + \frac{V_1^2}{2Jg_c} + \frac{Z_1}{J}\left(\frac{g}{g_c}\right) \right) = \frac{\dot{W}}{J} + \sum \dot{m}_2 \left(h_2 + \frac{V_2^{\,2}}{2Jg_c} + \frac{Z_2}{J}\left(\frac{g}{g_c}\right) \right)$$

Before delving into the definition of the equation's terms and variables, it would be first helpful to define a simple system, such as the following:



In this simple diagram a pipe has a continuously flowing fluid traveling through it between points 1 and 2. *By definition*, the control volume for our system is bound by a theoretical boundary at points 1 and 2 and the interior walls of the pipe to form an enclosure with a single entrance and single exit. The fluid has mass, so defined (and shaded) incremental mass $\mathbf{m_1}$ traveling at velocity $\mathbf{V_1}$ enters the control volume at point 1. At point 2 incremental mass $\mathbf{m_2}$ traveling at velocity $\mathbf{V_2}$ exits our control volume. Point 1 may be above or below point 2 with respect to an arbitrarily set horizontal datum and its relative height above this datum is defined as $\mathbf{Z_1}$ while point 2 is at $\mathbf{Z_2}$. Heat, defined as **Q** may enter our system while work, defined as **W,** may be withdrawn from it. Variables $\mathbf{m_1}$, $\mathbf{m_2}$, **Q**, and **W** are of singular absolute units each (e.g., the units for $\mathbf{m_1}$ and $\mathbf{m_2}$ are #m, and for **Q** and **W** BTU's) and to account for their respective time based rates of flow, each of these variables is indicated in the equation and diagram as a "dot" variable. Mass flow therefore is in units of #m per unit time, while heat and work will have units of BTU's per unit time.

By inspection, all other variables can be seen to relate to an energy definition. For example variable **h** is *enthalpy* which in itself is defined as $\mathbf{u + P \bullet \upsilon / J}$, where **u** is the intrinsic *internal energy* of the substance, a function of its temperature, with units of BTU/lbm. The term $\mathbf{P \bullet \upsilon / J}$ is the static pressure (lbf/ft^2) times the specific volume (ft^3/lbm) of the substance divided by conversion factor **J** (equal to 778 ft-lbf/BTU). The expression $\mathbf{P \bullet \upsilon / J}$ which also resolves into units of BTU/lbm is an *energy* term. Enthalpy therefore can be thought of as the total inherent molecular energy of the substance as it is constrained under pressure to result in an incremental "slug" of mass. Each $\mathbf{V^2/2Jg_c}$ expression represents the *kinetic energy* of the incremental mass slug at each of points 1 and 2. In this expression $\mathbf{V^2}$ is in units of ft^2/sec^2 and $\mathbf{(2Jg_c)^{-1}}$ is in units of (ft^2-lbf/lbm-BTU-sec^2)$^{-1}$. Each $\mathbf{Z/J \bullet (g/g_c)}$ expression represents the *potential energy* of the incremental mass slugs at points 1 and 2 due to their respective elevations above a zero height datum. In this expression **Z** is height in feet while $\mathbf{J^{-1} \bullet (g/g_c)}$ converts this potential energy of feet of height into units of BTU/lbm. Finally, as previously discussed, terms **Q** and **W** represent heat and work respectively, which are *energy*.

With inspection, considering *each* of the variables in the equation and the diagram it will become (hopefully) self evident that the *Steady State Thermodynamic Energy Equation* merely states the following:

- The sum of <u>all</u> mass entering the control volume <u>must equal</u> that exiting it, and
- The sum of <u>all</u> energy entering the control volume <u>must equal</u> that exiting it.

Through manipulation of several of the expressions in the *Thermodynamic Energy Equation*, resolving expressions into alternate (and uniform) units and by <u>assuming:</u>

- that $\mathbf{m_1}$ equals $\mathbf{m_2}$ (e.g., there is no "mass capacitance" in the system),
- $\mathbf{u_1}$ equals $\mathbf{u_2}$ (e.g., the intrinsic internal energies of masses $\mathbf{m_1}$ and $\mathbf{m_2}$ are equal),
- there is <u>no</u> heat transfer into or out of our control volume (e.g., **Q** is zero), and
- unproductive work *leaves* our system as <u>friction</u>, then

The *Thermodynamic Energy Equation* reduces to the following form:

$$\frac{P_1}{\gamma_1} + \frac{V_1^2}{2g} + Z_1 = \frac{P_2}{\gamma_2} + \frac{V_2^2}{2g} + Z_2 + HL$$

…which is readily identified as *Bernoulli's Equation* for incompressible (e.g., liquid) flow. This equation in essence states that for *equal mass flow* in and out of the system, the sum of all the energy components of that mass flowing in equals that flowing out minus the energy "lost" (as heat) by friction.

In *Bernoulli's Equation*, as before, subscripts **1** and **2** denote position 1 and 2 in our control volume. The term $\boldsymbol{\gamma}$ is equal to $\boldsymbol{\rho \bullet g_c}$ which is mass density (slugs/ft^3, equal to lbf-sec^2/ft^4) times the acceleration of gravity (32.17 ft/sec^2), resolving into units of lbf/ft^3. Pressure **P** remains in units of lbf/ft^2. The expression **HL** is defined as *head loss*. All other terms were previously defined.

When one "inspects" *Bernoulli's Equation* it becomes evident that the units for each expression are resolved into *feet*. The interpretation of such units is that each energy expression (including friction) is resolved into the equivalent amount of energy equal to that of the *potential energy of a column of the fluid of that height in feet*. Thus, Bernoulli's Equation is an energy equivalency equation, with it being implicitly understood that mass is also equilibrated between the entrance and exit points.

By this exercise it has been shown that the flow of all fluids is a thermodynamic process that conforms to the Laws of Newtonian Physics. As such, absent any system 'capacitance', the sum of all masses entering any system must equal that leaving and the sum of all energies entering the system must equal that leaving.