

Fundamental Laws of Motion for Particles, Material Volumes, and Control Volumes

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1 Basic laws for material volumes

1.1 Material volumes and material particles

Material systems behave according to universal physical laws. Perhaps the most ubiquitous of these are the law of mass conservation, Newton's laws of motion, and the first and second laws of thermodynamics, all of which were understood before the nineteenth century ended. In this chapter we review these four laws, starting with their most primitive forms, and show how they can be expressed in forms that apply to control volumes. These turn out to be very powerful tools in engineering analysis¹.

The most fundamental forms of these four laws are stated in terms of a *material volume*. A material volume contains the same particles of matter at all times². A particular material volume may be defined by the closed bounding surface that envelops its material particles at a certain time. Since every point of a material volume's bounding surface moves (by definition) with the local material velocity \vec{v} (Fig. 1), the shape of the volume at all other times is determined by the laws of dynamics.

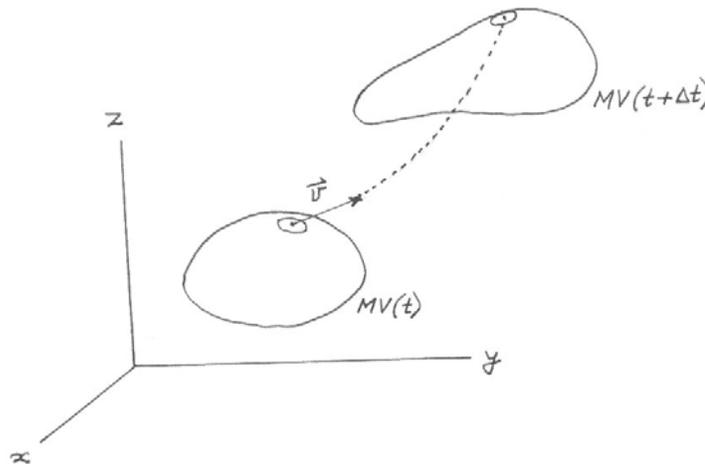


Fig. 1 A material volume moves with the material particles it encloses.

1.2 Laws for material particles

The simplest forms of the four basic laws apply to an infinitesimal *material particle* that is so small that the velocity \vec{v} , density ρ , thermodynamic temperature T , and other

¹ For a historical note on control volume analysis in engineering, see Chapter 4 of Walter G. Vincenti's *What Engineers Know and How They know It*, John Hopkins University Press, 1990.

² A material volume is the same as a "closed system" in thermodynamics.

intrinsic properties are essentially uniform within it. An observer moving with a particle (“sitting on it,” as it were) would see its properties change with time only (Fig. 2).

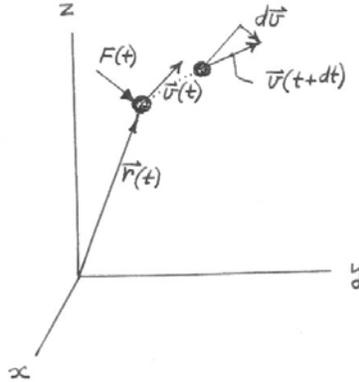


Fig. 2 Motion of a material particle between time t and time $t+\Delta t$

For a material particle with infinitesimal volume $\delta V(t)$, density $\rho(t)$, and velocity \bar{v} , the four laws have the following familiar forms:

Mass conservation

$$\frac{d}{dt}(\rho\delta V) = 0 \quad (1)$$

This law asserts that the mass $\delta M = \rho\delta V$ of a material particle remains invariant. (The prefix δ indicates quantities that are of infinitesimal size, and the prefix d refers to changes that occur in the indicated property in time dt .)

Newton's law of (non-relativistic) linear motion

$$(\rho\delta V) \frac{d\bar{v}}{dt} = \delta\bar{F}, \quad \text{or} \quad \frac{d}{dt}(\rho\bar{v}\delta V) = \delta\bar{F} \quad (2)$$

Newton's law states that, relative to an inertial reference frame³, the product of a particle's mass and acceleration is at every instant equal to the net force $\delta\bar{F}(t)$ exerted on it by the rest of the universe, or alternatively, that the rate of change of a particle's momentum (a vector quantity) is equal at every instant to the force applied to the particle by the rest of the universe. (Actually the law states that the rate of change of momentum is *proportional* to the applied force, with the coefficient being *universal*, but in most

³ An inertial reference frame is one in which the particle would move at a perceptibly constant velocity if all the forces acting on it were removed.

systems of measurement the universal coefficient is set equal to unity, which determines the units of force in terms of those of acceleration and time.)

Newton's law applied to angular motion

$$\frac{d}{dt}(\vec{r} \times \rho \vec{v} \delta V) = \vec{r} \times \delta \vec{F} \quad (3)$$

This law figures in rotary motion. The rate of change of a particle's angular momentum (the quantity in brackets on the left side of (3), $\vec{r}(t)$ being the particle's position vector) is at every instant equal to the net torque exerted on the particle by the rest of the universe. This is not a new law, but one that follows from Eq. (2). Equation (3) is obtained by taking the cross product of $\vec{r}(t)$ and Eq. (2), using Eq. (1), and noting that $d\vec{r}/dt \times \vec{v} = \vec{v} \times \vec{v} = 0$. Like the law it is derived from, Eq. (3) is valid only in inertial reference frames. Actually the law states that the rate of change of momentum is *proportional* to the applied force, with the coefficient being universal, but in most systems of measurement the universal coefficient is set equal to unity, which determines the units of force in terms of those of acceleration and time.

First law of thermodynamics

$$d(\rho e_i \delta V) = \delta W + \delta Q \quad (4)$$

The increase of a material particle's total energy in a time interval dt (e_i is its total energy per unit mass, internal plus kinetic plus potential) is equal to the work δW done in the interval dt by forces exerted by the rest of the universe on the material volume's *boundary* (that is, not counting work done by volumetric body forces), plus the heat δQ added to the particle at its boundary during this interval. Equation (4) is one part of the *definition* of the quantity we call heat.

Second law of thermodynamics

$$d(\rho s \delta V) \geq \frac{\delta Q}{T} \quad (5)$$

The increase of a particle's entropy (s represents the particle's entropy per unit mass) in a time dt is greater than or equal to the heat added to the particle at its boundary during this interval divided by the absolute (thermodynamic) temperature, T .⁴ The equality sign applies in the limit of a *reversible* process.

⁴ According to the Second Law the temperature in Eq. (5) should be that of the "reservoir" from which the heat is supplied to the material particle. In this case the heat comes from the material that bounds the infinitesimal particle, where the temperature differs infinitesimally from the particle's own average temperature T .

1.3 Laws for finite material volumes

From Eqs (1)-(5), which apply to an infinitesimal material particle, we can derive the laws for a finite material volume like the one sketched in Fig. 1. This is accomplished by applying a particular law to each of the material particles that comprise the volume under consideration, and summing. In the limit of a continuum, the sum can be viewed as an integral over the volume of material properties which are expressed as fields (that is, as functions of position \bar{r} and time t), consistent with the Eulerian way of describing material flows.

The result is the following set of *rate equations*⁵ for a material volume's mass, momentum, energy, and entropy:

Mass conservation

The mass contained in a material volume remains invariant,

$$\frac{d}{dt} \int_{MV(t)} \rho(\bar{r}, t) dV = 0, \quad (6)$$

where $\rho(\bar{r}, t)$ is the material's density field, $dV = dx dy dz$ represents a volume element inside the material volume, and $MV(t)$ under the integral sign signifies integration over the material volume at the instant t .

Motion (linear momentum)

$$\frac{d}{dt} \int_{MV(t)} \rho(\bar{r}, t) \bar{v}(\bar{r}, t) dV = \bar{F}_{MV}(t). \quad (7)$$

This is Newton's law of motion: The rate of increase of a material volume's momentum, evaluated by integrating the local momentum per unit volume $\rho\bar{v}$ over the material volume, is at every instant equal to the vector sum $F_{MV}(t)$ of all the forces exerted on the material volume *by the rest of the universe*. This force includes body forces acting on the material within the volume and surface forces acting at the boundary, but *not* the forces exerted between the various material particles within the volume, which cancel when the sum over all the constituent parts is taken—the action of one particle on another is exactly opposed by the reaction of the other on the first. It is

⁵ The usual term “conservation equation” is a bit of a misnomer, since mass is the only one of these quantities that is actually conserved.

understood that Eq. (7) applies only in inertial (non-accelerating) reference frames under non-relativistic conditions.

Motion (angular momentum)

$$\frac{d}{dt} \int_{MV(t)} \rho \bar{r} \times \bar{v} dV = \bar{T}_{MV}(t) = \sum_i \bar{r}_i \times \bar{F}_i \quad (8)$$

This equation is obtained by summing the angular momentum law for a material particle, Eq. (3), over all the particles that comprise a finite material volume. The law states that the rate of increase of a material volume's angular momentum, expressed as the integral over the volume of the angular momentum per unit volume, is equal to the vector sum $T_{MV}(t)$ of all torques exerted *by the rest of the universe* on the material volume. This form of the law assumes that the torques exerted between two particles within the volume are equal and opposite, or zero, which is the case except in rare circumstances. Note again that Eq. (8) is not a new law, but a corollary of Newton's law of motion and subject to the same restrictions.

First law of thermodynamics

$$\frac{d}{dt} \int_{MV(t)} \rho e_t dV = \dot{Q}_{MS}(t) + \dot{W}_{MS}(t), \quad (9)$$

This law is obtained by summing Eq. (4) over all the particles that comprise the material volume and noting that the particle-to-particle heat transfer and work terms cancel for all particles *inside* the material volume when the sum is taken (what comes from one goes into the other).

The law states that the rate of increase of a material volume's energy (e_t is the total energy per unit mass—internal plus kinetic plus gravitational) is equal to the sum of two “source terms” which represent interactions with the rest of the universe *at the volume's boundary*. The first source term is the net heat flow rate *into* the material volume across its bounding surface

$$\dot{Q}_{MS}(t) = - \int_{MS(t)} \bar{q} \cdot \bar{n} dA, \quad (10)$$

where

$$\bar{q} = -k\nabla T \quad (11)$$

is the conductive heat flux vector at a point on the material volume's boundary, k is the material's thermal conductivity, T is its local thermodynamic temperature, \bar{n} is the outward-pointing unit vector at the bounding surface, and dA is an elemental area on the bounding surface. The symbol $MS(t)$ denotes integration over the closed bounding surface of the material volume at time t . The second source term in (9) is the rate at which work is done by the rest of the universe *on* the material volume *at its boundary*. This may be evaluated as

$$\dot{W}_{MS}(t) = \int_{MS(t)} \bar{\sigma} \cdot \bar{v} dA \quad (12)$$

where $\bar{\sigma}$ is the vector stress exerted on the boundary by the rest of the universe and \bar{v} is the material's local velocity at dA . The quantity $\bar{\sigma} dA$ is the force exerted by the rest of the universe on the surface element dA of the control volume.

Equation (9) thus has the form

$$\frac{d}{dt} \int_{MV(t)} \rho e_i dV = - \int_{MS(t)} \bar{q} \cdot \bar{n} dA + \int_{MS(t)} \bar{\sigma} \cdot \bar{v} dA \quad (13)$$

Second law of thermodynamics

$$\frac{d}{dt} \int_{MV(t)} \rho s dV \geq - \int_{MS(t)} \frac{\bar{q} \cdot \bar{n} dA}{T} \quad (14)$$

The rate of increase of a material volume's total entropy is greater than or equal to the sum of all the local heat inflows at the boundary when each contribution is divided by the local *thermodynamic* (absolute) temperature at the point on the material volume's surface where the transfer takes place.

This law provides a *bounding value* of the rate of entropy increase, but not the actual value, and is less useful in dynamics than the other laws. It does, however, have some important uses in dynamics. One can for example discard from the dynamically possible solutions (those that satisfy mass conservation and the equation of motion) those that are unrealizable because they violate the Second Law, and one can predict the entropy change in limiting cases of negligible dissipation, where the equality sign applies.

2 The transformation to control volumes

2.1 The control volume

Equations (6)-(8) and (13)-(14) state universal laws that apply to all material distributions. They are, however, in a form that makes them ill suited for applications. Each equation contains a term of the form

$$\frac{d}{dt} \int_{MV(t)} \phi(\vec{r}, t) dV \quad (15)$$

in which a quantity $\phi(\vec{r}, t)$ that represents something per unit volume—mass, momentum, energy, or entropy—is first integrated over a material volume and the result then differentiated with respect to time. When the material is flowing and deforming, the volume’s boundary moves with it and is not known as a function of time until the problem is solved. It seems, therefore, that one must know the solution before one can apply these laws to find the solution. Clearly, we need to find a way of applying the basic laws to systems of our own choice, that is, to “control volumes.”

A *control volume* is an arbitrarily defined volume with a closed bounding surface (the control surface) that separates the universe into two parts: the part contained within the control volume, and the rest of the universe. The control surface is a mental construct, transparent to all material motion, and may be static in the chosen reference frame, or moving and expanding or contracting in any specified manner. The analyst specifies the velocity $\vec{v}_c(\vec{r}, t)$ at all points of the control surface for all time.

We shall show next how the universal laws for a material volume can be rewritten in terms of an arbitrarily defined control volume. This opens the way to the application of the integral laws in engineering analysis.

2.2 Rate of change of a volume integral over a control volume

We begin by considering a time derivative like Eq. (15) for a control volume rather than a material volume. The time rate of change of the integral of some field quantity $\phi(\vec{r}, t)$ over an arbitrarily defined control volume $CV(t)$ is by definition

$$\frac{d}{dt} \int_{CV(t)} \phi dV = \lim_{\Delta t \rightarrow 0} \frac{\int_{CV(t+\Delta t)} \phi(\vec{r}, t + \Delta t) dV - \int_{CV(t)} \phi(\vec{r}, t) dV}{\Delta t}. \quad (16)$$

The first integral on the right hand side is evaluated at the advanced time over the advanced volume, and the second is evaluated at time t over the volume at time t (Fig. 3). At any point \bar{r} we can write for small Δt

$$\phi(\bar{r}, t + \Delta t) = \phi(\bar{r}, t) + \frac{\partial \phi}{\partial t} \Delta t. \quad (17)$$

Inserting this into Eq. (15) we see immediately that

$$\frac{d}{dt} \int_{CV(t)} \phi dV = \int_{CV(t)} \frac{\partial \phi(\bar{r}, t)}{\partial t} dV + \lim_{\Delta t \rightarrow 0} \frac{\int_{CV(t+\Delta t)} \phi(\bar{r}, t) dV - \int_{CV(t)} \phi(\bar{r}, t) dV}{\Delta t} \quad (18)$$

where the integrals on the right are evaluated based on the values of $\partial \phi / \partial t$ and ϕ at time t . In the limit $\Delta t \rightarrow 0$, the difference between the two volume integrals in the second term can be evaluated (see Fig. 3) by means of an integral over the material surface at time t :

$$\int_{CV(t+\Delta t)} \phi(\bar{r}, t) dV - \int_{CV(t)} \phi(\bar{r}, t) dV = \int_{CS(t)} \phi(\bar{r}, t) \bar{v}_c \Delta t \cdot \bar{n} dA. \quad (19)$$

Here $\bar{v}_c(\bar{r}, t)$ is the velocity of the *control surface* element dA , \bar{n} is the outwardly-directed unit normal vector associated with dA , and $\bar{v}_c \cdot \bar{n} \Delta t dA$ is the control volume size increase in time Δt due to the fact that the surface element dA has moved in that time interval. The integral on the right side is taken over the entire (closed) bounding surface $CS(t)$ of the control volume.

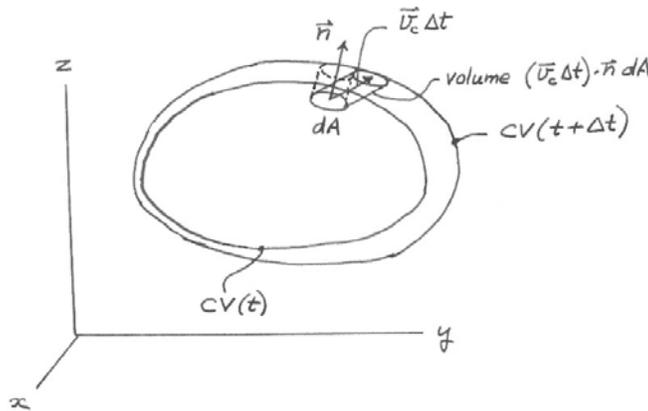


Fig. 3 Motion of a control volume between t and $t+\Delta t$ for small Δt .

Substituting Eq. (19) into Eq. (18), we obtain for an arbitrarily chosen control volume $CV(t)$,

$$\frac{d}{dt} \int_{CV(t)} \phi dV = \int_{CV(t)} \frac{\partial \phi(\vec{r}, t)}{\partial t} dV + \int_{CS(t)} \phi(\vec{r}, t) \vec{v}_c \cdot \vec{n} dA \quad (20)$$

2.3 Rate of change of a volume integral over a material volume

The corresponding equation for a material volume $MV(t)$ can be obtained simply by noting that a material volume is a control volume every point of which moves with the material velocity. Equation (20) thus applies to a material volume if we set the control volume velocity equal to the material velocity, $\vec{v}_c = \vec{v}$, and identify the limits of integration with the material volume. This yields for a material volume

$$\frac{d}{dt} \int_{MV(t)} \phi dV = \int_{MV(t)} \frac{\partial \phi(\vec{r}, t)}{\partial t} dV + \int_{MS(t)} \phi(\vec{r}, t) \vec{v} \cdot \vec{n} dA \quad (21)$$

2.4 Reynolds' material-volume to control-volume transformation theorem

Reynolds' transformation theorem provides a recipe for transforming the fundamental laws in Eqs. (6)-(8) and (13)-(14) to control volumes. The transformation theorem is obtained by considering a control volume at time t and the material volume which coincides with it at that instant. The control volume $CV(t)$ is chosen arbitrarily by defining its closed bounding surface $CS(t)$. The material volume is comprised of all the matter inside the control volume at time t (Fig. 4). The two volumes will of course diverge with time since the material volume wafts off with the particles to which it is "attached" and the control volume moves according to our specification. This is of no consequence since we are considering only a "frozen" instant when the two volumes coincide.

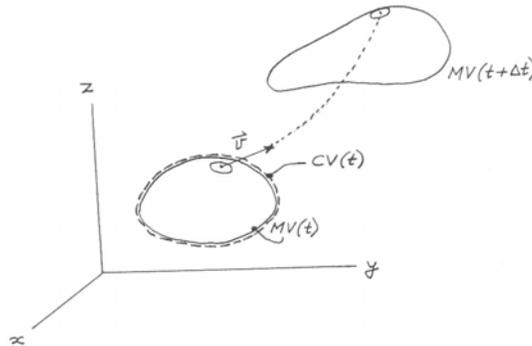


Fig. 4 The control and material volumes in the transformation theorem

We apply Eq. (20) to our CV and Eq. (21) to the MV that coincides with it at time t , and note that because the volumes coincide, the integrals on the right-hand side of Eq. (21) may be evaluated over either the CV instead of the MV . This yields two alternative equations for the time derivative of an integral over a material volume, expressed in terms of a CV that coincides with the material at the time involved:

$$\text{Form A} \quad \frac{d}{dt} \int_{MV(t)} \phi dV = \frac{d}{dt} \int_{CV(t)} \phi dV + \int_{CS(t)} \phi (\vec{v} - \vec{v}_c) \cdot \vec{n} dA \quad (22)$$

$$\text{Form B} \quad \frac{d}{dt} \int_{MV(t)} \phi dV = \int_{CV(t)} \frac{\partial \phi}{\partial t} dV + \int_{CS(t)} \phi \vec{v} \cdot \vec{n} dA \quad (23)$$

Equation (22) is obtained by subtracting Eq. (20) from Eq. (21). Equation (23) is Eq. (21) with the integrals referred to the CV instead of the MV , the two being coincident. Recall that \vec{v} is the local material velocity, \vec{v}_c is the local control surface velocity at the surface element dA , and \vec{n} is the *outward*-pointing unit normal vector associated with dA .

Both forms A and B are *valid for arbitrarily moving and deforming control volumes* (i.e. control volumes that may be expanding, translating, accelerating, or whatever), and for unsteady as well as steady flows. The two forms express exactly the same thing, but do the bookkeeping in different ways.

Remember that ϕ represents something per unit volume. Both forms express the material-volume time derivative on the left as a sum of two terms that refer to the control volume that coincides with the material volume at the instant t .

In form A, the first term on the right is the rate of change of the amount of ϕ inside the control volume at time t (the volume integral is evaluated first, then the time derivative), and the second term is the net rate of outflow of ϕ across the control volume's boundary.

In form B, the first term on the right is the volume integral of the *partial* time derivative of ϕ over the control volume at time t (the CS is held fixed at its position at time t while the integration is performed). The second term accounts for the fact that the material volume's boundary, which appears in the integral on the left, does not maintain the shape it has at time t , but envelops more volume (and more of the quantity ϕ) when it expands, every point moving with the local material velocity \vec{v} . *The control surface velocity does not enter at all in form B.*

We shall see that Form A is usually more convenient in unsteady applications than Form B. This is particularly true in cases where $\partial \phi / \partial t$ is singular at some surface inside the control volume (as it is at a moving flame front inside a solid-propellant rocket, for example, if ϕ is the material density distribution in the rocket), in which case it is difficult to evaluate the volume integral in Form B. The volume integral in Form A, on the other hand, can be calculated straightforwardly and then differentiated with respect to time.

3 Basic laws for control volumes

The basic physical laws expressed by Eqs (6)-(8) and (13)-(14) in material-volume terms are transferred to a control volume as follows. We transform the left sides by setting ϕ equal to either ρ , $\rho\bar{v}$, $\bar{r} \times \rho\bar{v}$, e_t , or s , in form A or form B of Reynolds' transformation theorem [Eqs. (22) and (23)]. The right hand sides are transformed by noting that since the *MS* and *CS* coincide at the instant being considered (see Fig. 4), the force, torque, and heat flow terms on the right hand side of Eqs (7)-(8) and (13)-(14) are the same for the *CV* as for the *MV*. Note, however, that the rate at which work is being done on the *CS* is *not* equal to the rate at which work is being done on the *MS* because these surfaces move at different velocities.

Two alternative forms are obtained for each equation, depending on whether Form A [Eq. (22)] or form B [Eq. (23)] of the transformation theorem is used. The alternative forms are expressions of the same physical law, stated in somewhat different terms. Both apply to *any* control volume at every instant in time no matter how the control surface is moving and deforming, provided the reference frame is one where the basic equations apply.

We remind the reader (see Fig. 3) that in what follows,

$$v_n = \bar{v} \cdot \bar{n} = v \cos \theta \quad (24)$$

is the outward normal component of the material's *absolute* velocity at the control surface, θ being the angle between \bar{v} and the outward-pointing normal unit vector \bar{n} , and

$$v_{rn} = (\bar{v} - \bar{v}_c) \cdot \bar{n} = v_n - v_{cn} \quad (25)$$

is the outward normal component of the material's velocity *relative to the control surface*, v_{cn} being the outward normal component of the control surface's velocity.

3.1 Mass conservation

Setting $\phi = \rho$ in Eqs. (22) and (23), we transform Eq. (6) into two alternative forms for a CV:

$$\text{Form A} \quad \frac{d}{dt} \int_{CV(t)} \rho dV + \int_{CS(t)} \rho v_n dA = 0 \quad (26A)$$

$$\text{Form B} \quad \int_{CV(t)} \frac{\partial \rho}{\partial t} dV + \int_{CS(t)} \rho v_n dA = 0 \quad (26B)$$

Equation (26A) states the mass conservation principle as follows: The rate of increase of the mass contained in the CV , plus the *net* mass flow rate out through the (generally *moving*) CS , equals zero at every instant.

Equation (26B) states the same principle in different but equally correct terms: The rate of increase of the mass contained in the *fixed* volume defined by the control surface at time t , plus the net mass outflow rate through the *fixed* bounding surface of that volume, equals zero at all times.

3.2 Linear momentum

Putting $\phi = \rho\bar{v}$ in Eqs. (22) and (23) and substituting into (7), we obtain the following alternative forms for the equation of motion applied to a CV :

$$\text{Form A} \quad \frac{d}{dt} \int_{CV(t)} \rho\bar{v}dV + \int_{CS(t)} \rho\bar{v}v_m dA = \bar{F}_{CV}(t) \quad (27A)$$

$$\text{Form B} \quad \int_{CV(t)} \frac{\partial(\rho\bar{v})}{\partial t} dV + \int_{CS(t)} \rho\bar{v}v_n dA = \bar{F}_{CV}(t) \quad (27B)$$

Here, $\bar{F}_{CV}(t)$ is the vector sum of all the forces exerted at time t by the rest of the universe on the control volume, including volumetric forces and stresses exerted on the control volume's boundaries. For a continuous distribution of surface and body forces,

$$\bar{F}_{CV}(t) = \int_{CS} \bar{\sigma}dA + \int_{CV} \rho\bar{G}dV \quad (28)$$

Equation (27A) states that the rate at which the linear momentum contained in the CV increases with time, plus the net flow rate of linear momentum *out* through the control surface, is equal at every instant to the force exerted by the rest of the universe on the material within the control surface.

Equation (27B) states it in different terms: The rate of increase of the momentum contained in a “frozen” volume identical to the control surface at time t , plus the net mass outflow rate through the “frozen” bounding surface of that volume, is equal at time t to the net force exerted by the rest of the universe on the material in the control volume.

3.3 Angular momentum

Setting $\phi = \rho\bar{r} \times \bar{v}$ in either (22) or (23) and substituting into (8) yields the angular momentum theorem for a CV in two alternative forms:

$$\text{Form A} \quad \frac{d}{dt} \int_{CV(t)} (\rho \vec{r} \times \vec{v}) dV + \int_{CS(t)} (\rho \vec{r} \times \vec{v}) v_n dA = \vec{T}_{CV}(t) \quad (29A)$$

$$\text{Form B} \quad \int_{CV(t)} \frac{\partial}{\partial t} (\rho \vec{r} \times \vec{v}) dV + \int_{CS(t)} (\rho \vec{r} \times \vec{v}) v_n dA = \vec{T}_{CV}(t) \quad (29B)$$

Here \vec{r} is the position vector from an arbitrary origin, $\vec{T}_{CV}(t)$ is the sum of all the torques (relative to the chosen origin) that the rest of the universe exerts on the control volume, including those resulting from both surface forces (pressure and shear) and volumetric body forces (e.g. gravity). An inertial reference frame is presumed. For a continuous distribution of surface and body forces,

$$\vec{T}_{CV}(t) = \int_{CS} \vec{r} \times \vec{\sigma} dA + \int_{CV} \rho \vec{r} \times \vec{G} dV. \quad (30)$$

where $\vec{\sigma}$ is the vector stress exerted on the boundary element dA by the rest of the universe, and \vec{G} is the body force exerted by the rest of the universe on unit mass of material within the volume.

Equation (29A) states the following: The rate at which the angular momentum inside the control volume increases with time, plus the net rate at which angular momentum flows out of the control surface, is equal to the net torque exerted by the rest of the universe on the matter in the control volume (on the boundary as well as on the mass within). The reader will be able to interpret (29B) based on the comments been made above with reference to (26B) and (27B).

3.4 First law of thermodynamics (energy equation)

Setting $\phi = e_i$ in Eqs. (22) and (23) and substituting into (13), we obtain two forms of the first law for a CV :

$$\text{Form A} \quad \frac{d}{dt} \int_{CV(t)} \rho e_i dV + \int_{CS(t)} \rho e_i v_n dA = - \int_{CS(t)} \vec{q} \cdot \vec{n} dA + \int_{CS(t)} \vec{\sigma} \cdot \vec{v} dA \quad (31A)$$

$$\text{Form B} \quad \int_{CV(t)} \frac{\partial(\rho e_i)}{\partial t} dV + \int_{CS(t)} \rho e_i v_n dA = - \int_{CS(t)} \vec{q} \cdot \vec{n} dA + \int_{CS(t)} \vec{\sigma} \cdot \vec{v} dA \quad (31B)$$

Equation (31A) states that the rate at which the total energy contained in the CV increases with time, plus the net rate at which total energy flows out of the CS , is equal to the sum of two terms on the right. The first term is the rate at which heat is conducted *into* the CV via the control surface. The second is the rate at which the rest of the

universe does work *on* the *material volume* whose bounding surface coincides with the *CS* at the instant in question. The work done at the *control surface*,

$$\dot{W}_{CS}(t) = \int_{CS(t)} \vec{\sigma} \cdot \vec{v}_c dA , \quad (32)$$

depends on the control surface velocity distribution, which is chosen at will by the analyst and obviously has no place in a universal law.

3.5 Second law of thermodynamics

$$\text{Form A} \quad \frac{d}{dt} \int_{CV(t)} \rho s dV + \int_{CS(t)} \rho s v_n dA \geq - \int_{CS(t)} \frac{\bar{q} \cdot \bar{n}}{T} dA \quad (33A)$$

$$\text{Form B} \quad \int_{CV(t)} \frac{\partial(\rho s)}{\partial t} dV + \int_{CS(t)} \rho s v_n dA \geq - \int_{CS(t)} \frac{\bar{q} \cdot \bar{n}}{T} dA \quad (33B)$$

Equation (33A) states that the rate of increase of the entropy contained in the *CV* (*s* is the entropy per unit mass), plus the net rate of entropy convection out of the control surface, never exceeds the integral over the control surface of the normal heat influx divided by the local absolute temperature.

4 Procedure for control volume analysis

The application of any one of the integral laws involves consideration of the following nine steps:

Step 1

Choose the reference frame in which the problem is viewed and velocity and other properties are measured. If Newton's law is involved in the problem, the reference frame must be an inertial (non-accelerating) frame.

Step 2

Choose your control volume by specifying its (closed) bounding surface at some instant (e.g. $t=0$) and at all times thereafter. The control surface *must* be closed. It may be multiply connected. It may move in the chosen reference frame and expand and distort as it does so. All this is your choice. If the CS runs parallel to a fluid-solid interface, take care to specify whether your control surface is just on the fluid side, or just on the solid side. It *must be on one side or the other*, so that quantities like ρ , \vec{v} , e_p , etc. have well defined values.

Step 3

Write down the integral law that you wish to apply.

Step 4

Identify the values of the properties ($\rho, \vec{v}, \vec{v}_c, e_t, \vec{\sigma}, \vec{q}$, and s , or whichever of them figure in your problem) at every element dA of the control surface and calculate the surface integrals that appear in your integral equations. Select the control volume so that the bounding surface passes as much as possible through regions where you know the properties, or can deduce them. Wherever you don't know some quantities, introduce them as unknowns, expecting to determine them as you proceed.

Step 5

Identify the values of ρ, \vec{v}, e_t, s and \vec{G} at every volume element dV inside the control volume, and evaluate the volume integrals in your integral equations.

Step 6

Calculate the time derivative of the volume integral that appears on left-hand side of your integral equation.

Step 7

From steps 4, 5 and 6, substitute into your integral equations.

Step 8

If you set out to solve a practical problem using the control volume theorems, you must write down enough equations to ensure that their number equals the number of unknowns in the equations. The four integral laws that we have described are totally general and rigorous, but these laws contain more unknowns than equations. You will need to draw also on other physical laws, e.g. gravitational theory and/or electromagnetic field theory to define the external body force field, and various constitutive equations (e.g. the thermodynamic equations of state, the form of the stress tensor, etc.).

In most applications you will also *make simplifying approximations* wherever they are appropriate. Uniform flow over inlet and exit planes is a typical engineering approximation; integral relations by themselves provide no information about velocity distributions. If you have reason to believe that the flow may be approximated as inviscid, you invoke Bernoulli's equation⁶ and when you have obtained your solution check that it is consistent with that approximation. If you that density varies little, you write $\rho = \text{constant}$ and later check that this approximation is justified, based on the fluid's thermal equation of state and the predicted pressure excursion in your problem.

Step 9

Solve for the unknowns

Step 10

Check, by suitable order-of-magnitude estimates, that your solution is consistent with any approximations that you made.

⁶ Bernoulli's equation is derived from Newton's law of motion, just like the linear momentum theorem. By invoking Bernoulli, we are *not* simply writing down the same equation twice. The linear momentum equation *applies generally*, to viscous and inviscid flows. By introducing Bernoulli's equation we add the *additional* constraint that the flow is inviscid.

Appendix 1: Summary of Fundamental Laws

Material particles

Mass conservation $\frac{d}{dt}(\rho\delta V) = 0$

Motion (linear momentum) $(\rho\delta V)\frac{d\bar{v}}{dt} = \delta\bar{F}$ or $\frac{d}{dt}(\rho\bar{v}\delta V) = \delta\bar{F}$

Motion (angular momentum) $\frac{d}{dt}(\bar{r} \times \rho\bar{v}\delta V) = \bar{r} \times \delta\bar{F}$

First law of thermodynamics $d(\rho e_t \delta V) = \delta W + \delta Q$

Second law of thermodynamics $d(\rho s \delta V) \geq \frac{\delta Q}{T}$

Material volumes

Mass conservation $\frac{d}{dt} \int_{MV(t)} \rho dV = 0$

Motion (linear momentum) $\frac{d}{dt} \int_{MV(t)} \rho\bar{v}dV = \bar{F}_{MV}(t)$

Motion (angular momentum) $\frac{d}{dt} \int_{MV(t)} \rho\bar{r} \times \bar{v}dV = \bar{T}_{MV}(t)$

First law of thermodynamics $\frac{d}{dt} \int_{MV(t)} \rho e_t dV = \dot{Q}_{MS}(t) + \dot{W}_{MS}(t)$

Second law of thermodynamics $\frac{d}{dt} \int_{MV(t)} \rho s dV \geq - \int_{MS(t)} \frac{\bar{q} \cdot \bar{n} dA}{T}$

Control volumes

Reynolds' theorem

$$\frac{d}{dt} \int_{MV(t)} \phi dV = \int_{CV(t)} \frac{\partial \phi}{\partial t} dV + \int_{CS(t)} \phi \bar{v} \cdot \bar{n} dA$$

Mass conservation

$$\text{Form A} \quad \frac{d}{dt} \int_{CV(t)} \rho dV + \int_{CS(t)} \rho (\bar{v} - \bar{v}_c) \cdot \bar{n} dA = 0$$

$$\text{Form B} \quad \int_{CV(t)} \frac{\partial \rho}{\partial t} dV + \int_{CS(t)} \rho \bar{v} \cdot \bar{n} dA = 0$$

Linear momentum

$$\text{Form A} \quad \frac{d}{dt} \int_{CV(t)} \rho \bar{v} dV + \int_{CS(t)} \rho \bar{v} v_n dA = \bar{F}_{CV}(t)$$

$$\text{Form B} \quad \int_{CV(t)} \frac{\partial (\rho \bar{v})}{\partial t} dV + \int_{CS(t)} \rho \bar{v} v_n dA = \bar{F}_{CV}(t)$$

Angular momentum

$$\text{Form A} \quad \frac{d}{dt} \int_{CV(t)} (\rho \bar{r} \times \bar{v}) dV + \int_{CV(t)} (\rho \bar{r} \times \bar{v}) v_n dA = \bar{T}_{CV}(t)$$

$$\text{Form B} \quad \int_{CV(t)} \frac{\partial (\rho \bar{r} \times \bar{v})}{\partial t} dV + \int_{CS(t)} (\rho \bar{r} \times \bar{v}) v_n dA = \bar{T}_{CV}(t)$$

First law

$$\text{Form A} \quad \frac{d}{dt} \int_{CV(t)} \rho e_t dV + \int_{CS(t)} \rho e_t v_n dA = - \int_{CS(t)} \bar{q} \cdot \bar{n} dA + \int_{CS(t)} \bar{\sigma} \cdot \bar{v} dA$$

$$\text{Form B} \quad \int_{CV(t)} \frac{\partial (\rho e_t)}{\partial t} dV + \int_{CS(t)} \rho e_t v_n dA = - \int_{CS(t)} \bar{q} \cdot \bar{n} dA + \int_{CS(t)} \bar{\sigma} \cdot \bar{v} dA$$

Second law

$$\text{Form A} \quad \frac{d}{dt} \int_{CV(t)} \rho s dV + \int_{CS(t)} \rho s v_n dA \geq - \int_{CS(t)} \frac{\bar{q} \cdot \bar{n}}{T} dA$$

$$\text{Form B} \quad \int_{CV(t)} \frac{\partial (\rho s)}{\partial t} dV + \int_{CS(t)} \rho s v_n dA \geq - \int_{CS(t)} \frac{\bar{q} \cdot \bar{n}}{T} dA$$

Definition of velocities

\bar{v} = local fluid velocity in an inertial reference frame

\bar{v}_c = local control surface (CS) velocity in same frame

$\bar{v}_r = \bar{v} - \bar{v}_c$ = fluid velocity *relative to local CS*

v_n = outward normal component of \bar{v}

v_m = outward normal component of \bar{v}_r

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