KLM Technology Group
P. O. Box 281
Bandar Johor Bahru,
80000 Johor Bahru,
Johor, West Malaysia

Kolmetz Handbook Of Process Equipment Design

SOLID AND FLUID MECHANICS FUNDAMENTALS

(ENGINEERING DESIGN GUIDELINES)

Co Author:
Reni Mutiara Sari

Editor / Author
Karl Kolmetz

TABLE OF CONTENTS

INTRODUCTION 9

Scope 9

General Consideration 10

A. Aspects of Solid Mechanics 10

- Statics 10
- Dynamics 11
- General Laws 11

B. Aspect of Fluid Mechanics 11

- Fluid Statics 13
- Fluid Dynamic 14
- Types of Fluid 15
- Streamlines and Stream-tube 16
- The Laws of Thermodynamics 16

DEFINITIONS 18

NOMENCLATURE 19

Greek letters 21

THEORY 22

A. Solid Mechanics 22

I. Fundamental of Solid Mechanic Statics 22

Vectors 22

Characteristics of Vector 22

Statics of Rigid Bodies 25

a. Resultant of Forces Acting on a Body at the Same Point 25

b. Lami’s Theorem 26

c. Resultant of Any Number of Forces Applied to a Rigid Body at the Same Point 27

d. Moment of The Force 28

e. Couple 30

f. Equilibrium of Rigid Bodies 31

g. Support of Rigid Bodies 32

h. Center of Gravity 34

i. Centroid of Plane Area 34

j. Centroids of Composite Areas 35

k. Moment of Inertia 37

II. Fundamental of Solid Mechanic Dynamics 43

Kinematics of Particles 43

a. Rectilinear Motion 43

b. Circular and Curvilinear Motion 46

Kinematics of a Rigid Body 50

a. Motion of a Rigid Body in a Plane 51

Dynamics of a Particle 53

a. Newton's Second Law of Motion 53

b. Principle of Work and Energy 54

c. Conservation of Energy 55

d. Principle of Impulse and momentum 55

e. Conservation of Momentum 56

f. Principle of Angular Impulse and Momentum 57

Dynamics of Rigid Bodies 59

a. Equation of Motion for the Center of Mass 59

b. Rotation about a Fixed Axis Not Through the Center of Mass 59

c. General Plane Motion 60

d. Work and Energy Methods for Rigid Bodies in Plane Motion 60

e. Impulse and Momentum of a Rigid Body 61

f. D' Alembert's Principle 62

Friction 63

a. Static and Dynamic Friction 64

b. Friction on an Inclined Plane 65

c. Rolling Friction 66

d. The Wedge 67

Vibration 67

a. Definition of Simple Harmonic Motion 68

b. Free Undamped Vibration 69

c. Forced Undamped Vibrations 70

d. Free Damped Vibration 72

e. Forced Damped Vibrations 75

B. Fluid Mechanics 76

I. Fluid Properties 76

II. Fluid statics 79

a. The Basic Equation of Fluid Statics 79

b. Pressure-Sensing Device 81

c. Hydrostatic Forces on Submerged Plane Surface 82

d. Buoyancy 85

e. Stability of Submerged and Floating Bodies 86

f. Compressible Flow 87

III. Fluid Dynamic 88

a. Flow rate 88

b. Law of the Conservation of Mass 89

c. Law of the Conservation of Energy 91

d. The Power of a Stream of Fluid 94

e. Principle of Thermodynamics 94

f. Conservation of Momentum 96

h. Incompressible Pipe Flow 100

1. Flow Regimes 100

2.Parameters for Pipe Flow 101

REFERENCES 108

LIST OF TABLE

Table 1 : position of centroids of some plane geometrical 34

Table 2 : moment of inertia 42

Table 3 : values of friction coefficient for various materials 65

Table 4: summary of processes in an ideal gas 96

Table 5 : absolute roughness of pipe 103

Table 6 : equivalent length in pipe diameters (L_{eq}/D) of various valves and fittings 104

Table 7 : resistant coefficient of enlargement and contraction pipe 105

LIST OF FIGURE

Figure 1 : schematics to describe the shear stress in fluid mechanics 12

Figure 2 : deformation characteristics of substances 13

Figure 3 : pressure relation 14

Figure 4 : streamlines and stream-tube 16

Figure 5: vectors addition 22

Figure 6: triangle of forces 23

Figure 7: resultant of two forces 25

Figure 8 : Lami's theorem 26

Figure 9 : three-dimensional components of a vector R 27

Figure 10 : moment of the force 28

Figure 11 : moment of a bound vector about a point 29

Figure 12 : a couple 31

Figure 13 : a beam to determine reaction 33

Figure 14 : a bridge to determine reaction 33

Figure 15 : composite area divided into simple areas 35

Figure 16: a planar surface of area 38

Figure 17 : parallel axis based on area and mass 39

Figure 18 : polar moment of inertia 40

Figure 19 : relation between product of inertia and parallel-axis 41

Figure 20 : space-time graph 44

Figure 21 : velocity-time graph 45

Figure 22 : normal and tangential accelerations 48

Figure 23 : illustration of polar coordinates 49

Figure 24 : types of rigid body motion 50

Figure 25 : illustration for instantaneous center of rotation 52

Figure 26 : general motion of a rigid body. 52

Figure 27 : impact 56

Figure 28 : angular impulse and momentum 58

Figure 29 : rotation of a rigid body about a fixed axis 59

Figure 30 : Impulse and Momentum of a Rigid Body 61

Figure 31 : illustration of occured friction on a block 63

Figure 32 : free-body diagram of motion up an inclined plane 65

Figure 33 : illustration of rolling friction 66

Figure 34 : free-body diagram of wedge 67

Figure 35 : Simple harmonic motion 68

Figure 36 : free undamped vibration 69

Figure 37 : forced undamped vibration 70

Figure 38 : curve of resonance 71

Figure 39 : illustration of free damped vibration 72

Figure 40 : forced damped vibration 75

Figure 41 : magnification factor in damped forced vibration 76

Figure 42 : pressure equivalence 79

Figure 43 : manometer 81

Figure 44 : notation for liquid force on submerged plane surface 82

Figure 45 : notation for liquid force on submerged curved surface 84

Figure 46 : buoyancy force diagram 85

Figure 47: Stability for a submerged body 86

Figure 48 : Stability for a floating body 87

Figure 49 : An arbitrarily shaped control volume 90

Figure 50 : continuity 91

Figure 51 : process flow diagram for conservation of energy 93

Figure 52 : P-V and T-S diagrams 94

Figure 53 : thermodynamic processes in an ideal gas 9

Figure 54 : a conduit in the x direction only 98

Figure 55 : fluid entering at point 1 and leaving at point 2. 99

Figure 56 : viscous flow around an airfoil 106

Figure 57 : drag coefficient for spheres, cylinders, and disks 107

INTRODUCTION

Scope

Solid mechanics is the study of the deformation and motion of solid materials under the action of forces, temperature changes, phase changes, and other external or internal agents. It is one of the fundamental applied engineering sciences in the sense that it is used to describe, explain and predict many of the physical phenomena.

Solid mechanics is typically useful in designing and evaluating tools, machines, and structures, ranging from wrenches to cars to spacecraft. The required educational background for these includes courses in statics, dynamics, and related subjects. For example, dynamics of rigid bodies is needed in generalizing the spectrum of service loads on a car, which is essential in defining the vehicle's deformations and long-term durability.

Fluid mechanics deals with the study of all fluids under static and dynamic situations. Fluid mechanics is a branch of continuous mechanics which deals with a relationship between forces, motions, and statistical conditions in a continuous material. This study area deals with many and diversified problems such as fluid statics, flow in enclose bodies, or flow round bodies (solid or otherwise), flow stability, etc.

Both solid mechanics and fluid mechanics play very important roles in design. Because a fluid cannot resist deformation force, it moves, or flows under the action of the force. Its shape will change continuously as long as the force is applied. Whereas, a solid can resist a deformation force while at rest. While a force may cause some displacement, the solid does not move indefinitely.

Solid mechanics which is based on Newton laws, either in rest or motion. Solid mechanics consist of several fundamentals such as vectors, moments, couple, moment inertia, motion, vibration, and rigid bodies in statics and dynamics. Fluid mechanics consist of fluid properties and hydrostatic forces along with their application in nature.

General Consideration

A. Aspects of Solid Mechanics

The theory of solid mechanics starts with the particle, and then a rigid body. Rigid body mechanics is usually subdivided into statics and dynamics.

Statics

Statics are the study of materials at rest. The actions of all external forces acting on such materials are exactly counterbalanced and there is a zero net force effect on the material: such materials are said to be in a state of static equilibrium. Equilibrium is said to be stable when the body with the forces acting upon it returns to its original position after being displaced a very small amount from that position; and neutral when the forces retain their equilibrium when the body is in its new position.

If a body is supported by other bodies while subject to the action of forces, deformations and forces will be produced at the points of support or contact and these internal forces will be distributed throughout the body until equilibrium exists. They are equal in magnitude and opposite in direction to the forces with which the supports act on the body, known as supporting forces. The supporting forces are external forces applied to the body[6].

A material body can be considered to consist of a very large number of particles. A rigid body is one which does not deform, in other words, the distance between the individual particles making up the rigid body remains unchanged under the action of external forces. An example of the statics of a rigid body is a bridge supporting the weight a car.

Dynamics

There are two major categories in dynamics, kinematics and kinetics. Kinematics involves the time and geometry-dependent motion of a particle, rigid body, deformable body, or a fluid without considering the forces that cause the motion. It relates position, velocity, acceleration, and time. Kinetics combines the concepts of kinematics and the forces that cause the motion.

Dynamics of a rigid body follows Newton's second law. Newton's second law of motion states that the body will accelerate in the direction of and proportional to the magnitude of the resultant R. In rectilinear motion, the acceleration and the direction of the unbalanced force must be in the direction of motion. Forces must be in balance and the acceleration equal to zero in any direction other than the direction of motion. An example of the dynamics of rigid body is an accelerating and decelerating elevator.

General Laws

The fundamental concepts and principles of mechanics follow the relation between the motion and the force that is defined by Newton's Law. Newton's law states that:

1. A body remains at rest or continues in a straight line at a constant velocity unless acted upon by an external force.
2. A force applied to a body accelerates the body by an amount which is proportional to the force.
3. Every action is opposed by an equal and opposite reaction.

B. Aspect of Fluid Mechanics

Fluid mechanics is a study of the relationships between the effects of forces, energy and momentum occurring in and around a fluid system. Fluids are substances capable of following and taking the shape of containers. Fluids can be classified as liquids or gases; liquids are incompressible, occupy definite volumes, and have free surfaces; whereas, gases are compressible and expand until they occupy all portions of the container. Fluids cannot sustain shear or tangential forces when in equilibrium.

Substances may be classified by their response when at rest to the imposition of a shear force. Liquid that undergoes a shear stress between a short distance of two plates can be shown in Figure 1.

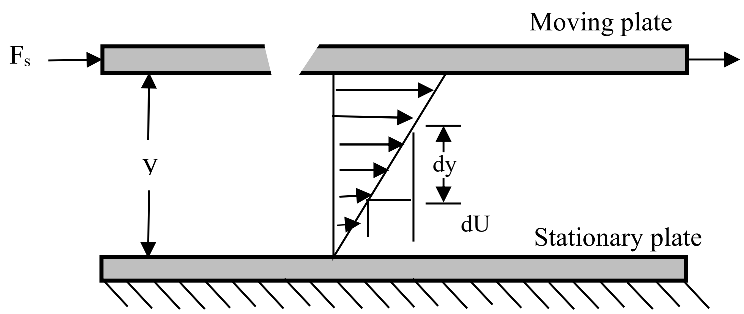


Figure 1 : schematics to describe the shear stress in fluid mechanics

The deformation characteristics of various substances are divided to five characteristics as illustrated in figure 2. An ideal or elastic solid will resist the shear force, and its rate of deformation will be zero regardless of loading and hence is coincident with the ordinate. A plastic will resist the shear until its yield stress is attained, and the application of additional loading will cause it to deform continuously, or flow.

If the deformation rate is directly proportional to the flow, it is called an ideal plastic. Newtonian fluid is real fluids which have internal friction so that their rate of deformation is proportional to the applied shear stress. If it is not directly proportional, it is called a non-Newtonian fluid.

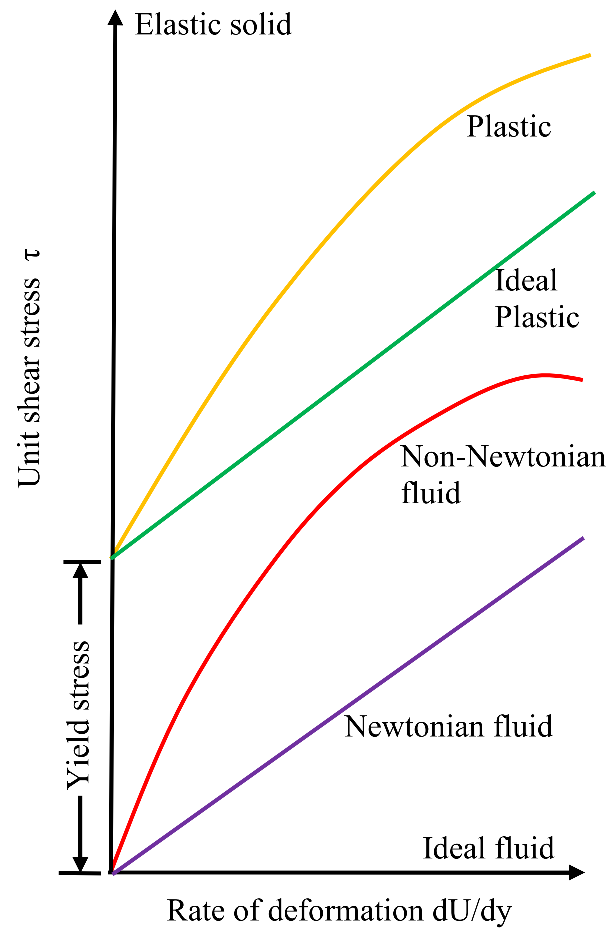


Figure 2 : deformation characteristics of substances

Fluid Statics

In a static fluid, an important property is the pressure in the fluid. Pressure is defined as force exerted by a mass under the influence of gravity and a mass of fluid on a supporting area, or force per area. The fluid pressure acts normal to any plane and is transmitted with equal intensity in all directions. In fluid mechanics and in thermodynamic equations, the units are lbf/ft^2, but engineering practice is to use units of lbf/in^2.

Most fluid-mechanics equations and all thermodynamic equations require the use of absolute pressure, and unless otherwise designated, a pressure should be understood to be absolute pressure. Common practice is to denote absolute pressure as lbf/ft^2 abs, or psfa, lbf/in^2 abs or psia; and in a like manner for gauge pressure lbf/ft^2 g, lbf/in^2 g, and psig. The relationship between absolute pressure, gauge pressure, and vacuum is shown in Figure 3 [6].

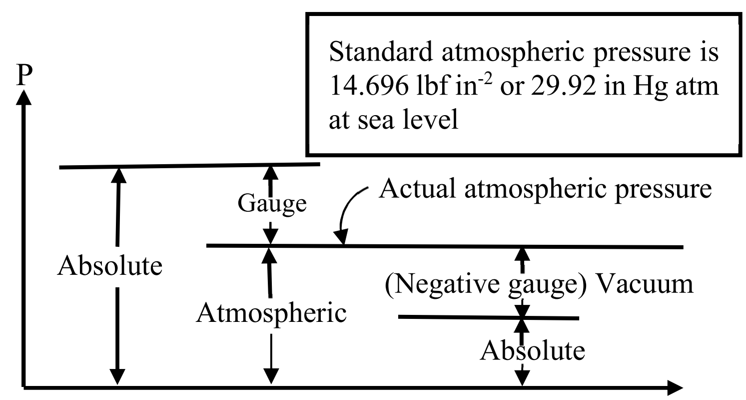


Figure 3 : pressure relation

Fluid Dynamics

Fluid dynamics is a sub-discipline of fluid mechanics that deals with fluid flow – natural science of fluid in motion. The elements of a flowing fluid can move at different velocities and can be subjected to different accelerations. The following principles apply in fluid flow:

a. The principle of conservation of mass, from which the equation of continuity is developed.
b. The principle of kinetic energy, from which some flow equations are derived.
c. The principle of momentum, from which equations regarding the dynamic forces exerted by flowing fluids can be established.

Types of Fluid

Fluid flow can be characterized as steady or unsteady, uniform or non-uniform. There typically can classify any flow as follow.

1. Steady uniform flow

   Conditions do not change with position in the stream or with time. An example is the flow of water in a pipe of constant diameter at constant velocity.

2. Steady non-uniform flow

   Conditions change from point to point in the stream but do not change with time. An example is flow in a tapering pipe with constant velocity at the inlet - velocity will change as moving along the length of the pipe toward the exit.

3. Unsteady uniform flow

   At a given instant in time the conditions at every point are the same, but will change with time. An example is a pipe of constant diameter connected to a pump pumping at a constant rate which is then switched off.

4. Unsteady non-uniform flow

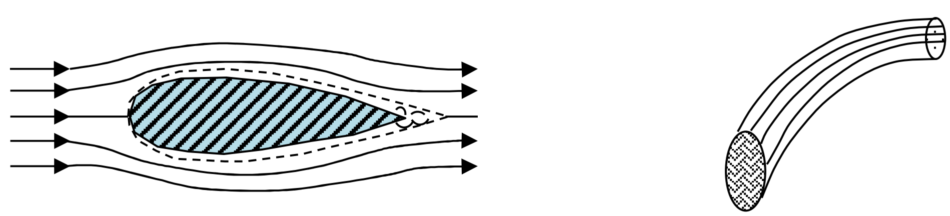
   Every condition of the flow may change from point to point and with time at every point. For example waves in a channel.

In additional, there are also considered about number of dimensional required to describe the velocity profile.

1. Flow is one dimensional, if the flow parameters (such as velocity, pressure, depth etc.) at a given instant in time only vary in the direction of flow and not across the cross-section.
2. Flow is two-dimensional, if it can be assumed that the flow parameters vary in the direction of flow and in one direction at right angles to this direction. Streamlines in two-dimensional flow are curved lines on a plane and are the same on all parallel planes. The example is area.
3. All flows take place between boundaries that are three-dimensional. Typically, it takes three directions of flow such as x, y, z as a volume of fluid in a circular pipe.

Streamlines and Stream-tube

A streamline is a line which gives the direction of the velocity of a fluid particle at each point in the flow stream. When streamlines are connected by a closed curve in steady flow, they will form a boundary through which the fluid particles cannot pass. The space between the streamlines becomes a stream tube. They can be illustrated in figure 4.



(a) streamlines around a wing (b) stream-tube

Figure 4 : streamlines and stream-tube

The Laws of Thermodynamics

The First Law of Thermodynamics

This is a law of energy conservation. It states that energy is always conserved, it cannot be created or destroyed. In essence, energy can be converted from one form into another[9]. The increase in internal energy of a closed system can be defined as follows.

$$Q - W = \Delta U \qquad \text{Eq (1)}$$

Where,

Q = heat transfer, Btu (kJ)
W = work transfer, Btu (kJ)
ΔU = increase in internal energy, Btu (kJ)

For a thermodynamic cycle of a closed system, which returns to its original state, the heat Q_{in} supplied to a closed system in one stage of the cycle, minus that Q_{out} removed from it in another stage of the cycle, equals the net work done by the system. Work done by a system is considered positive; $W > 0$. Work done on a system is considered negative; $W < 0$.

The Second Law of Thermodynamics

It might be thought that the first law of thermodynamics permits all the heat transfer to a cycle to be returned as work transfer, but unfortunately the second law places restraints on the achievement of this desirable situation. It states that in all energy exchanges, if no energy enters or leaves the system, the potential energy of the state will always be less than that of the initial state. This is also commonly referred to as entropy. Entropy is a measure of disorder[13].

DEFINITION

Angular displacement - a particle moves on a circular path its angle of rotation (or its angular displacement) θ, varies with time.

Boundary layer - thin layer of fluid adjacent to a surface where viscous effects are important; viscous effects are negligible outside the boundary layer.

Buoyancy - is based on Archimedes' principle, which states that the buoyant force exerted on a submerged body is equal to the weight of the displaced fluid.

Center of gravity - the point through which the whole weight of a body may be assumed to act.

Couple - pair of two equal and opposite forces acting on a body in a such a way that the lines of action of the two forces are not in the same straight line.

Drag coefficient - force in the flow direction exerted on an object by the fluid flowing around it, divided by dynamic pressure and area.

Energy - the capacity of a body to do work by reason of its motion or configuration.

Entropy - a measure of the disorder of any system, or of the unavailability of its heat energy for work.

Force - the action of one body on another which will cause acceleration of the second body unless acted on by an equal and opposite action counteracting the effect of the first body.

Friction - the resistance that is encountered when two solid surfaces slide or tend to slide over each other.

Impulse - the product of the force and the time that force acts

Inertia - property of matter which causes a resistance to any change in the motion of a body.

Isentropic - one condition for which there is no heat transfer in reversible between the system and surroundings, therefore this process is also adiabatic.

Lift coefficient - force perpendicular to the flow direction exerted on an object by the fluid flowing around it, divided by dynamic pressure and area.

Linear momentum - the product of mass and the linear velocity of a particle and is a vector.

Metacenter - the point at which the line of action of the buoyancy force cuts the vertical center line of the floating body in the displaced position.

Moment of the force - the turning effect of a force on a body.

Polar moment of inertia - the sum of the moments of inertia about any two axes at right angles to each other in the plane of the area and intersecting at the pole.

Potential energy - the energy possessed by an element of fluid due to its elevation above a reference datum.

Rigid body - one in which the particles are rigidly connected that does not deform, or change shape.

Resonance - characteristic through increasing amplitude to infinity. The resonance phenomenon appears when the frequency of perturbation or forced angular frequency, p is equal to the natural angular frequency ω.

Steady uniform flow - conditions do not change with position in the stream or with time.

Streamline - a line which gives the direction of the velocity of a fluid particle at each point in the flow stream.

Separation - phenomenon that occurs when fluid layers adjacent to a solid surface are brought to rest and boundary layers depart from the surface contour, forming a low pressure wake region. Separation can occur only in an adverse pressure gradient.

Transition - change from laminar to turbulent flow within the boundary layer.

Vector - a directed line segment that has both magnitude and direction.

Viscosity - a measure of the resistance fluids to flow and may be considered as internal friction.

NOMENCLATURE

A	sectional area, ft^2 (m^2)
a	total angular acceleration, rad/s^2
c	actual damping coefficient, N.s/m
c_{cr}	critical damping coefficient, N.s/m
C_D	drag coefficient, dimensionless
Cv	constant volume heat capacity, Btu/lbmol.°F (J/mol.K)
d	distance, ft (m)
dv	velocity differential, ft/s (m/s)
dy	distance differential, ft (m)
f	frequency, Heartz (rad/s)
F	force, lbf (N)
F_B	buoyant force, lbf (N)
F_D	drag force, lbf (N)
F_H	normal force on the vertical projection, lbf (N)
F_0	amplitude of the forced vibration, dimensionless
F_V	weight of fluid above the curve, lbf (N)
g	acceleration gravitional, 32.2 ft/s^2 (9.81 m/s^2)
h	height above the ground, ft (m)
H	head, ft (m)
H_1	enthalpy at point 1, btu/lb (J/kg)
H_2	enthalpy at point 2, btu/lb (J/kg)
h_A	head added, ft (m)
h_L	head loss, ft (m)
h_E	head extracted, ft (m)
H_O	angular momentum about O, ($kg.m^2/s$)
I	moment of inertia, $lbm.ft^2$ ($kg.m^2$)
k	radii of gyration, ft (m)
k	spring stiffness, N/m
KE	kinetic energy, J (N.m)
m	mass, lb (kg)
M	moment, lbf.ft (Nm)

MF_i mole fraction of component *i*
MW_i molecular weight of component *i*, lb/ft^3 (kg/m^3)
P power, HP (watt)
PE potential energy, J (N.m)
Q energy added, Btu/lb (J/kg)
r radius of circular path, ft (m)
R gas law constant, 10.731 ft^3.lb$_f$/in^2.lbmol °R (8314.34 kg.m^2/s^2.kgmol.K)
s space or displacement, ft (m)
S entropy, btu/lbm.°F (kJ/kg.K)
T period, sec/cycle
T temperature, °R (K)
U internal energy, btu (J)
v angular velocity, rad/s
v velocity, ft/s (m/s)
V volume, ft^3 (m^3)
W weight, lbf (N)
W work, J (N.m)
Ws net mechanical work, Btu/lb (J/kg)
z elevation or depth, ft (m)

Greek letters

$\dot{m}$	mass flow rate, lbm/s (kg/s)
α	angle of inclination, degree
α	angular acceleration, rad/sec^2
α	kinetic energy velocity correction factor
a_n	normal acceleration, rad/s^2
a_t	tangential acceleration, rad/s^2
β	momentum velocity correction factor
ε	absolute roughness, in (mm)
$\sum F$	total of force, lbf (N)
$\sum F$	frictional losses, Btu/lb (J/kg)
δ	polytropic index
θ	angular displacement, rad
ω	angular velocity, rad/s
ω_d	damped natural frequency, Hz (rad/s)
ζ	damping factor, ratio c/c_{cr}
ρ	radius of curvature of the path, ft (m)
τ	shear force, lb/ft.s^2 (N/m^2)
μ	viscosity, lbf.s/ft^2 or poise (N.s/m^2)
μ_m	gas mixture viscosity, micropoise (N.s/m^2)
ν	kinematic viscosity, ft^2/s or stoke (m^2/s)
γ	specific weight, lbf/ft^3 (N/m^3)
γ	specific heat ratio, Cp/Cv