where the component distribution varies in space and in time in a statistically "non-stationary" manner, such as the flows mentioned above (Beck *et al.* 1986). It does require a substantial amount of digital data processing power, but this is becoming inexpensive with the development of array processors such as the INMOS "Transputer."

Flow imaging is similar to medical tomographic imaging in which by using externally-mounted sensors an image of a cross-section of the body can be obtained. However, in medical imaging the sensing system must be moved axially along the body to obtain a "multi-slice" cross-section, whereas in flow imaging the flow field moves along the pipe so that a single image plane is sufficient to characterize the flow. In flow imaging the velocity of each of the components over the cross-section of the pipe must be measured and this may be done by cross correlation of information from two image planes spaced along the axis.

Referring to Fig. 7, the specific subsystems for flow imaging are:

(a) the fluid flow field which we assume is composed of two or more separate components (liquid–gas, gas–solid, and the like),

(b) the sensors and sensor electronics,

(c) image reconstruction which includes extraction of image characteristics (e.g., edge enhancement) and the heuristic, mathematical, or linguistic methods to construct the image,

(d) image interpretation to give the instantaneous concentration of the components in the flow, and

(e) cross correlation of pixel information from two identical imaging systems spaced axially along the pipe (not shown in Fig. 7) in order to obtain the velocity profile over the pipe cross-section.

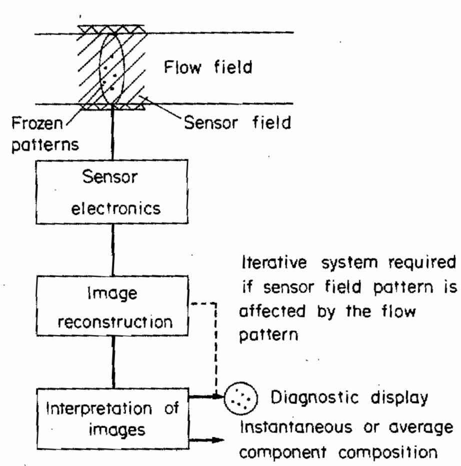


***Figure 7***
Subsystems for flow imaging

The mass flow rate of each component is then derived from the integral giving the cross-sectional area occupied by the component weighed by the velocity of the component and its density (Beck *et al.* 1986).

*See also:* Fluid Flow Control; Control Valve Sizing; Servovalves, Electrohydraulic; Flow Measurement: Flow and Volumetric Rate; Flow Measurement, Quantity

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## Flow Network Ascendency and Self-Organization in Living Systems

Network ascendency quantifies the size and internal structure of a living system. Increases over time in size and in the quality of internal structure are regarded as growth and development, respectively. Self-organization, the ability of a living system to arrange itself into a coherent unity or functioning whole, because it encompasses these dual attributes of growth and development, may thereby be identified with increasing network ascendency.

A living system may be described as an ensemble of constituent parts which interact with one another by exchanging energy and materials. Though by no means obvious, it is assumed that these exchange networks are sufficient to describe the system thermodynamically. In a reductionistic vein one might wish to explain each individual flow (effect) in terms of conditions at the donor and receptor compartments (cause), but if positive feedback (cybernetic) loops dominate system kinetics, cause and effect become difficult to separate. It becomes sufficient to describe the more perceptible entity—the flow.

As in input–output analysis, the size of an arbitrary compartment (node) $i$ has meaning only in terms of the total amount of medium $T_i$ flowing through that component. The size of the whole network is then described as the sum of all the individual throughputs, or the total system throughput:

$$T = \sum_i T_i \tag{1}$$

To describe the extent to which the components function as a whole, one begins by asking the question "How does the throughput at component $i$ directly affect the throughput at another specific component $j$?" If the network is highly organized, knowing the throughput at a given node in the network will tell us much about what is happening at specific locations elsewhere in the system. The question posed above, then, is best addressed using quantities defined in information theory.

If $Q_i = T_i/T$ is the probability that an arbitrary quantum of medium is flowing through component $i$, and $f_{ij}$ is the conditional probability that the same quantum proceeds directly to become part of throughput $T_j$, then, on average, the amount we know about the other throughputs in the system once we measure that of any chosen compartment is quantified by the average information (Rutledge *et al.* 1976) as

$$A = T \sum_i \sum_j f_{ij} Q_i \log\left( f_{ij} \Big/ \sum_k f_{kj} Q_k \right) \tag{2}$$

Information measures are usually defined so as to include an arbitrary scalar multiplier. In the above formula the scalar was chosen to be the total system throughput. The quantity $A$ so defined is thereby the product of a size factor multiplied by a factor describing network organization. It is called the network ascendency (Ulanowicz 1980), and was chosen so as to give quantitative meaning to the notion of self-organization. In addition, the common intuition that those networks which possess the best combination of both size and structure are those most likely to survive competitors (real or putative) gives rise to the hypothesis that living networks develop over time so as to optimize network ascendency.

The mathematical form for ascendency possesses at least one upper bound, consideration of which gives rise to several ancillary variables useful in quantifying other phenomena associated with self-organization. It can be demonstrated mathematically that the quantity

$$C = -T \sum_i Q_i \log Q_i \tag{3}$$

always exceeds or equals the ascendency (i.e. $C \geqslant A \geqslant 0$). The summand, in turn, is limited by the number of compartments ($T \log N \geqslant C$, where $N$ is the number of components). Therefore, an increasing number and greater diversity of compartments both relax the ultimate limits to ascendency. $C$ is called the development capacity.

However, not all the development capacity can appear as ascendency in any real situation. In large part this is due to the second law of thermodynamics. Not all the compartmental throughput can continue on as input to other components. A certain fraction of $T_i$, say $r_i$, must always become inaccessible to the given system (and to any other comparable system) during the processing of medium by component $i$. In addition a fraction $e_i$ may be lost or exported from the given system, but may serve as useful input to another comparable system. The amounts of the development capacity encumbered by these losses are

$$S = -T \sum_i r_i Q_i \log Q_i \quad (4)$$

and

$$E = -T \sum_i e_i Q_i \log Q_i \quad (5)$$

called the network dissipation and tribute, respectively.

The dissipation represents the effect of transfers of medium down the hierachical spectrum, whereas the tribute measures the effect on system development due to the possibility that the system being studied is but one component in a larger system (i.e., transfers up the hierarchical scale). The dissipation will always be nonzero as a consequence of thermodynamics; the tribute may not disappear in the course of development, if positive-feedback pathways exist in the higher-order system back into the inputs to the original system.

The fate of all the medium has now been accounted for ($\Sigma_j f_{ij} + r_i + e_i = 1$), but algebra shows that a residual, $C - (A + S + E) \geqslant 0$, may exist. The form of the remainder,

$$R = -T \sum_i \sum_j f_{ij} Q_i \log\left[f_{ij} Q_i \Big/ \left(\sum_k f_{kj} Q_k\right)\right] \quad (6)$$

reveals that it characterizes the average redundancy of flow pathways between any two arbitrary compartments. Specialization accompanies any increase in ascendency which occurs at the expense of network redundancy. However, too small a level of pathway redundancy can leave the network highly vulnerable to perturbations along the remaining critical pathways. It appears likely, therefore, that self-organizing networks evolve so that the residual redundancy reflects the level of environmental perturbations to which the system is being subjected.

The variables portraying the course of self-organization obey the relation

$$A = C - (S + E + R) \quad (7)$$

which parallels the definitions of the Gibbs and Helmholtz free energies—just as all the internal energy of a system cannot be made available for useful work, so all of the development capacity of a network cannot appear as coherent structure. Some development capacity will always be encumbered as overhead (S + E + R) to meet thermodynamics, hierarchical and environmental demands.

The five network variables provide a convenient lexicon with which to discuss the phenomenon of self-organization in a more quantitative fashion. The hypothesis of maximal ascendency has yet to receive sufficient empirical testing. It has the potential, however, of becoming a holistic principle guiding self-organization in ecosystems, organisms, meteorological systems, economic networks and wherever else growth and development may occur.

*See also:* Ecosystem Compartment Modelling; Energy Systems in Ecology

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## Flowcharting in Computing

In the computer program design and development process one needs a method of expressing the algorithm in some preliminary form. A widely used tool is the program flowchart.

A flowchart is a pictorial representation of the logic used to solve a particular problem. It is a diagram illustrating the sequence of steps (instructions) that must be executed to arrive at the solution to a problem.

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## Fluid Flow Control

In process industries the flow rates of materials are tied most intimately to running economy and product quality. It is important to know the flow rates and to be able to set them to desired values. For this purpose, flow control is needed. Flow in closed conduits is most commonly encountered; open channels are more uncommon and are not dealt with in this article.

The flow process is very fast when compared to other types of processes in the process industries, and the dynamics of a flow control loop is usually defined by the flow control equipment; mainly by the actuator, but also by the measuring equipment. The control loop is mostly nonlinear because the gain varies according to the flow rate.

The greatest part of this article is devoted to the static behavior of control valves.

### *1. Measurement of Flow*

Measuring fluid flow in closed conduits is one of the most frequent tasks in process industries. However, the states and flow rates of fluids vary greatly so there are many different methods of measuring flow, each of which have their own best areas of application.

Most of the methods show some clear random fluctuation or noise about the correct measured value. There are very few research reports published about signal noise properties of flow measurement methods. Catheron and Hainsworth (1956) state that most noise occurs at frequencies above 3 Hz in orifice-plate measurement. In a study carried out at Tampere University of Technology, Finland, concerning vortex shedding flowmeters, it has been stated that for the fluctuation interval to include 95% of measurement values within the limit ±2% of average value, a measuring time of about 1 s is needed at maximum flow rate and about 10 s at 5% flow rate, when the fluid is water. When measuring flow of liquid, a low-pass filter with a time constant of 1–5 s is needed, or the filter must be a natural feature of the measuring device.

## 2. Dynamics of the Flow Process

We assume first that the flowing fluid is incompressible and that the volume of the flow channel does not vary. These assumptions hold good in cases of liquid flow in process control applications, where the high-frequency oscillations due to compressibility and elasticity can be ignored because of the slowness of the control system.

The movement of flowing fluid is dependent on the differential pressure between the ends of the flow channel, the hydrostatic pressure and pump head pressure, pressure drops in flow resistances and inertial forces of the flowing medium. For the differential equation of mass flow rate $\dot{m}$ in circular conduits we obtain

$$\ddot{m}\sum_i l_i/A_i+\frac{\dot{m}^2}{2\rho}\left[\sum_i \xi_i l_i/(d_i A_i^2)+\sum_j \zeta_j/A_j^2\right]=\Delta_p \tag{1}$$

where $\ddot{m}$ is the time derivative of mass flow rate, $l_i$ is the length of flow path section $i$, $A_i$ is the cross-sectional area of flow path section $i$, $\rho$ is the density of flowing fluid, $\xi_i$ is a dimensionless head-loss coefficient of the tube section $i$, $d_i$ is the inner diameter of tube section $i$, $\zeta_j$ is a dimensionless head-loss coefficient of local flow resistance $j$ and $\Delta p$ is the sum of differential pressures causing the flow. We can also write

$$\Delta p = \Delta p_S + g\rho\Delta h + \Delta p_P \tag{2}$$

where $\Delta p_S$ is the differential pressure measurable between the ends of the flow path, $g\rho\Delta h$ is the hydrostatic pressure developing in the flow path and $\Delta p_P$ is the pressure head of the pumps.

Here we assume that flow does not change direction, i.e., $\dot{m} \geqslant 0$. If $\Delta p$ is constant, we obtain the steady-state solution of this nonlinear differential equation when we set $\ddot{m} = 0$.

If the cross section of the flow channel is everywhere equal and Eqn. (1) is linearized, we obtain

$$T\Delta\ddot{m} + \Delta\dot{m} = \Delta(\Delta p)AT/l \tag{3}$$

where the time constant $T$ is given by

$$T = m_P \Big/ \left[\dot{m}_0(\xi l/d + \sum_i \zeta_i)\right] \tag{4}$$

where $m_P = \rho l A$ (the mass of fluid in the tube) $\dot{m}_0 = A(2\rho\Delta p_0)^{1/2}/(\xi l/d + \Sigma_i\zeta_i)^{1/2}$ (flow rate in the steady state), or

$$T = m_P v_0/(2A\Delta p_0) = \rho l v_0/(2\Delta p_0) \tag{5}$$

where $v_0$ is the average velocity of flow.

In Eqns. (4) and (5) the slight flow-rate dependence of the tube resistance coefficient has not been considered. Values of time constant are usually of the order of 1 s or fractions of it for tube lengths below 100 m.

## 3. Control Valves

The most common final control element in the control of flow is a control valve, which is an alterable local flow resistance. Figure 1 represents a typical construction of a globe-type control valve. Instead of head-loss coefficient, a control valve is characterized by a flow coefficient (International Electrotechnical Commission 1978, 1980):

$$A_v = Q(\rho/\Delta p_v)^{1/2} = \dot{m}/(\rho\Delta p_v)^{1/2} \tag{6}$$

where $A_v$ is the flow coefficient, $Q$ is the volumetric flow rate, $\Delta p_v$ is the pressure differential across the control valve and $\rho$ is the density of the flowing fluid.

We can obtain a relation between the local head-loss coefficient of a valve $\zeta_v$ and the flow coefficient $A_v$:

$$\zeta_v = 2(A/A_v)^2 \tag{7}$$

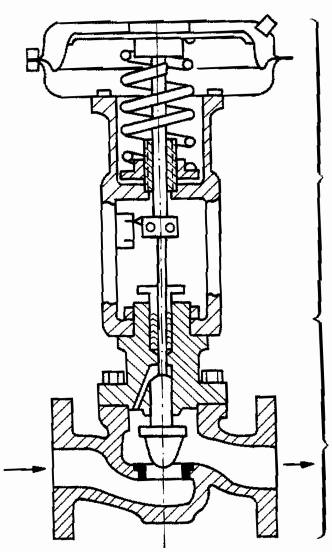


***Figure 1***
(a) Control valve and (b) actuator, normally-open combination