AVERAGING LIQUID LEVEL CONTROL

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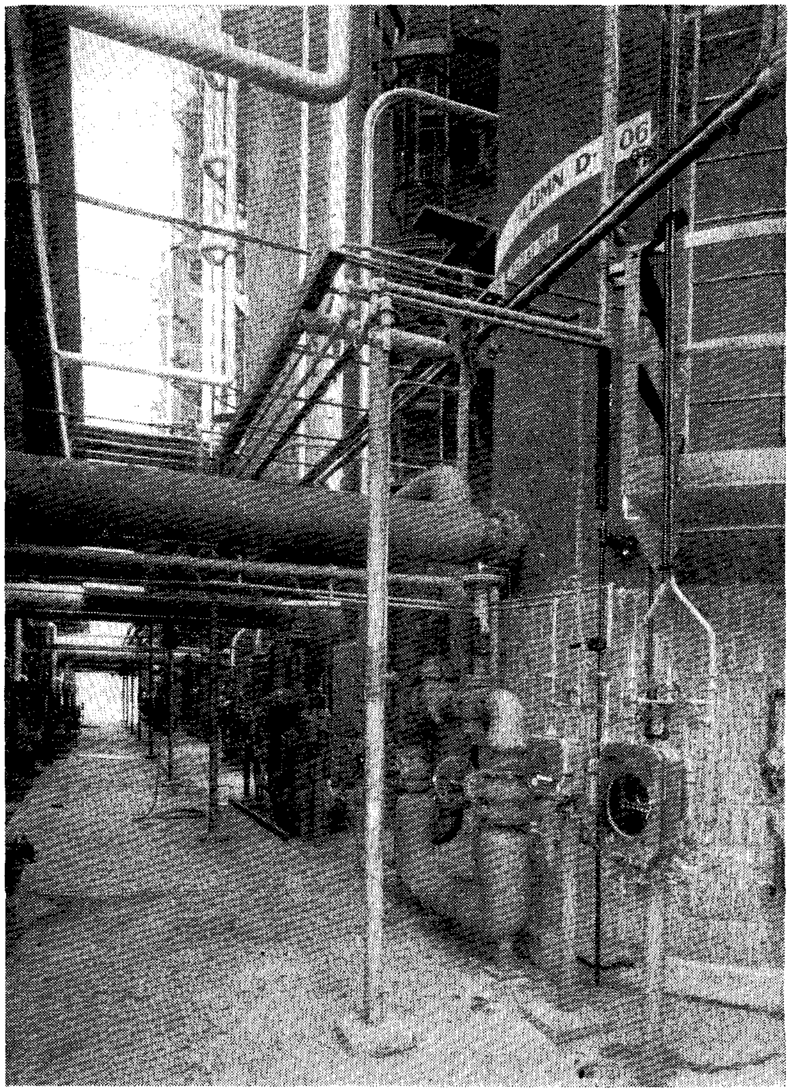
A logical method is presented for determining such factors as the required feed tank capacity, the type of instrumentation required, and the probable instrument settings for specific, continuous process installations of averaging liquid level controls. The photograph on this page shows a liquid level controller (right) installed at the base of a large fractionating column. →



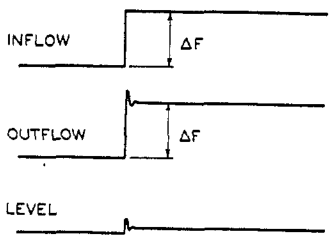


Figure 1. Effect of Flow on Liquid Level in a Fractionating Column

IN AUTOMATIC control of industrial processes the problem is usually one of maintaining a variable as close as possible to some optimum value. The process factors which cause deviations from the desired set point of the controller are the unavoidable variations in process demand called "load changes". When these changes occur, the controller corrects at the expense of a deviation for a certain length of time, and the best settings of the controller responses are those which hold the deviations and their duration to a minimum. But there are examples of automatic control in which deviation of the measured variable is not so detrimental to successful process operation as the abrupt disturbances in flow which a controller can make in correcting for load changes. The most common case of this kind is probably that of surge vessel control.

In the base of a fractionating column it is customary to install a liquid level controller which operates a valve in the line carrying bottom product away from the column. The actual liquid level carried in the column base is not important so long as it does not fall below the top of the heating surface or does not rise high enough to flood the bottom plate; therefore the controller set point is normally positioned for a level somewhere between these two limits. Level control itself is generally very easy. In the example cited, the controller could be set so that very small changes in level would make large output changes. When so adjusted, the course of level and flow transients following a sudden increase in column downflow would be about as shown in Figure 1. Level would be held essentially constant, and the outflow transient would almost duplicate the inflow transient. The sudden change in bottom-product outflow would matter little if the material were flowing to a storage tank; but if it were fed to another column in which control was important, the sudden change in feed flow might make operation of the second column difficult or impossible. In that case it would be much better to change the outflow slowly, to allow the level in the base of the first column to vary within the tolerable limits. This is called "averaging control".

Controllers of two types are used for averaging control—the simple proportional response type and the proportional plus reset type. The results obtainable with each and the optimum response settings are discussed in this paper. To state the problem, let us assume that the tolerable change of volume in a surge tank is C gallons; an inflow varying from 0 to Q gallons per minute enters the tank, and a level controller operates a valve in the outflow line as shown in (Figure 2). Optimum controller settings will be taken as those which, following the largest normal sudden change of inflow, ΔF, cause an outflow transient with the lowest possible maximum rate of change of outflow $(dF)_{max}$.

PROPORTIONAL RESPONSE CONTROLLER

To ensure that the level does not exceed minimum or maximum limits, a proportional response controller would be adjusted so that a level change equivalent to C would move the valve enough to change the outflow from 0 to Q gallons per minute (Figure 3). The sensitivity would then be:

$$S = Q/(m)(v)(C) \quad (1)$$

where S = controller sensitivity, lb./sq. in. output change per in. of pen travel
Q = maximum inflow and outflow, gal./min.
m = measuring sensitivity, in. of pen movement per gal. in tank
v = valve sensitivity, gal./min. change in outflow per lb./sq.-in. change in controller output
C = tank capacity between limits, gal.

For example, if a change in controller output of 8 lb./sq. in. opened a diaphragm valve from the closed position to the one at which Q gallons per minute passed, and the tolerable level change were equivalent to 4 inches of pen travel, the sensitivity would be set at 2 lb./sq. in. per in. It should be noted that the optimum sensitivity is not necessarily equivalent to 100% "throttling range", since a control valve will generally pass more than the maximum required flow at full opening.

With a proportional response controller set in the optimum sensitivity, the greatest rate of change of outflow will occur immediately after the largest sudden change in inflow, ΔF, and will be equal to:

$$(dF)_{max} = \frac{(\Delta F)(Q)}{C} \text{ gal./min./min.} \quad (2)$$

The outflow will change exponentially until it equals the inflow, as Figure 4 shows. The time constant of the level and outflow curves is equal to C/Q minutes.

PROPORTIONAL PLUS RESET CONTROLLER

When the sudden changes in inflow, ΔF, are small compared to the maximum throughput, Q, considerable reduction in $(dF)_{max}$ can be effected by the use of a proportional plus reset controller. The action of this instrument is such that under steady-flow conditions the level is maintained midway between the limits. Following a sudden sustained change in inflow, the tank level changes but is gradually set back to mid-tank, ready for the next inflow change in either direction.

In order to arrive at realistic optimum settings on this type of averaging controller, it is necessary to assign for the largest normal sudden inflow change, ΔF, the value which can occur every hour or so, not that which happens once a week or month. For example, in starting a piece of equipment, the flow might suddenly be changed from 0 to 200 gallons per minute; but once in continuous operation, no sudden changes in flow greater than 30 gallons per minute would ever occur even though the throughput during a week or month run might vary gradually over a very wide range. The largest normal sudden change in inflow, ΔF, in this case would be 30 gallons per minute.

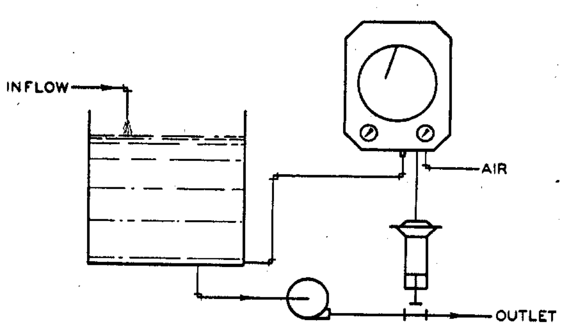
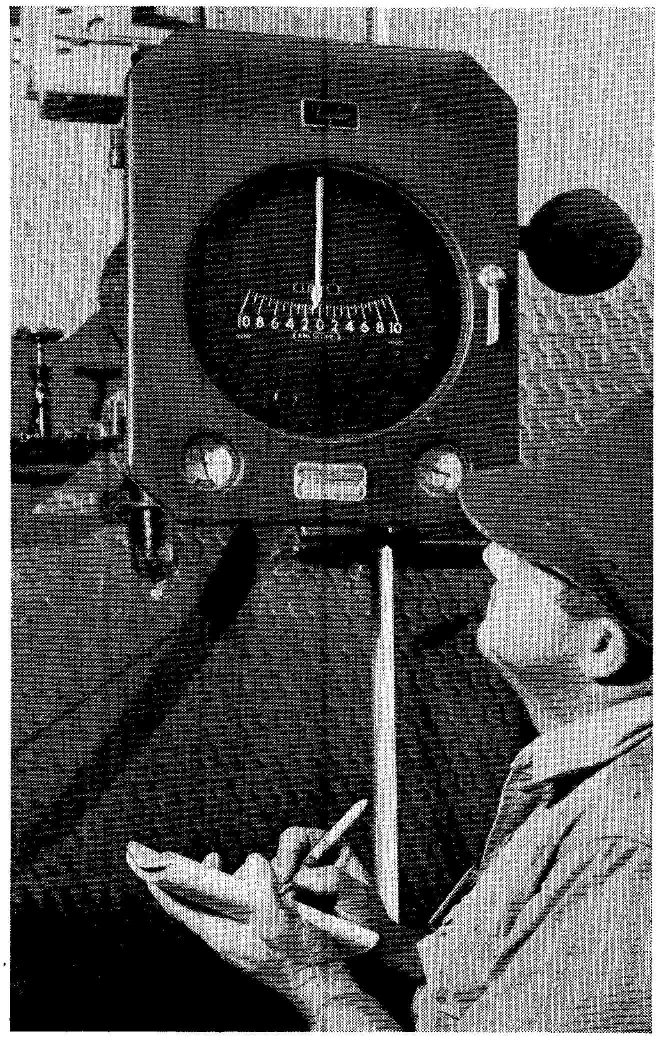


Figure 2. Simple Control System for Liquid Level

The optimum settings for the proportional plus reset controller are taken as those which produce the lowest maximum rate of outflow change following the largest normal sudden inflow change. In order to make the fullest use of the available tank volume, the controller should allow the level to rise just to the tank limit following this largest normal inflow change, ΔF.

Inflow changes larger than ΔF could cause the tank level to exceed its limits, were it not for limit stops built into the controller which automatically bring the outflow equal to inflow when either limit is reached. This modification of a standard proportional plus reset controller has been called an "averaging liquid level controller".



An Averaging Controller

The theoretical minimum rate of change of outflow following the largest inflow change, ΔF, would be:

$$(dF)_{max} = \frac{(\Delta F)^2}{C} \text{ gal./min./min.} \quad (3)$$

This would be realized if the controller increased the outflow at a constant rate, the two flows balancing just as the level reached the upper or lower limit. It is possible to adjust a proportional plus reset controller so that the maximum rate of outflow change

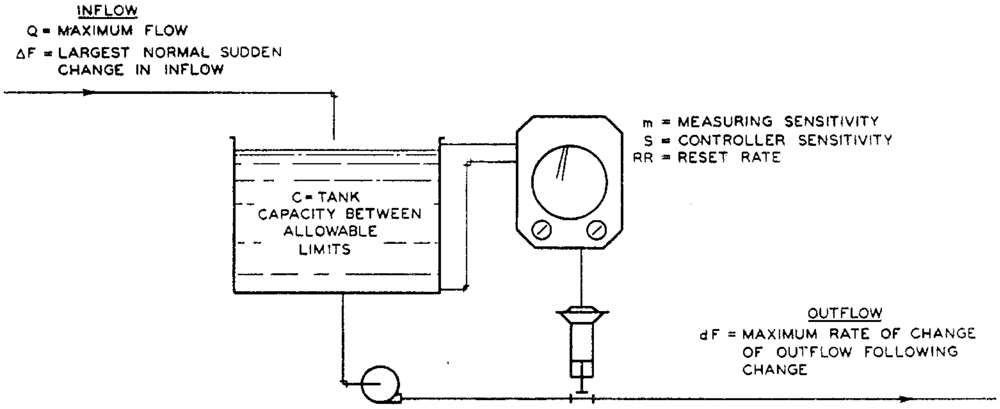


Figure 3. Diagram for Determining Controller Sensitivity

exceeds the theoretical value by a negligible amount. Nichols[1] solved this problem and found that the rate is only 3.6% greater than the theoretical.

At the optimum settings the level and flow transients following the largest normal sudden inflow change would be as shown in Figure 5, and these settings for proportional response sensitivity S and automatic reset rate RR are very nearly:

$$S = \frac{\Delta F}{(m)(v)(C)} \text{ lb./sq. in. per in.} \tag{4}$$

$$RR = (1.5)\frac{\Delta F}{C} \text{ per minute} \tag{5}$$

Or more simply, the sensitivity should be set so that a pen movement equivalent to the total allowable level change makes a valve movement sufficient to increase the outflow ΔF gallons per minute. The reset rate is set equal to 1.5 divided by the time required to fill the tank between allowable limits at a rate of flow equal to ΔF. This time unit is useful in work on averaging control and is:

$$\theta = C/\Delta F \text{ minutes} \tag{6}$$

COMPARISON OF CONTROLLER TYPES

Equations 2 and 3 show that the rate of change of outflow achieved by a proportional plus reset controller will be only $\Delta F/Q$ times as great as that from a proportional response instrument. If maximum throughput were 100 gallons per minute and the largest normal sudden inflow change were 10 gallons per minute, the controller with reset response would reduce $(dF)_{max}$ to one tenth that obtainable without reset. By the same reasoning, the tank volume necessary for a reset instrument would only be $\Delta F/Q$ times that for the simpler form.

Whenever the sudden changes in flow are less than the maximum throughput, a proportionate advantage is realized by the addition of reset response either in reducing the rate of change of outflow or in reducing the required tank size. However, there are certain disadvantages attending the use of the proportional plus reset instrument which can sometimes outweigh the advantages of smoother outflow or smaller equipment.

Overpeak. Figure 2 shows that the proportional response instrument does not allow the outflow change to exceed the inflow change, but that the reset type of instrument allows the outflow to exceed inflow in order that the level can be returned to the middle of the tank (Figure 5). This overpeak amounts to about 0.38 ΔF; ordinarily it is not serious but could be intolerable if the unit fed by the outflow were very near its maximum capacity—e.g., a column near the flooding point.

[1] Nichols, N. B., Am. Assoc. Advancement Sci., Gibson Island Instrumentation Conference, 1942.

Limits. The averaging type of liquid level controller has stops which prevent the level from exceeding allowable limits. When inflow changes larger than ΔF occur, these stops operate to balance inflow and outflow abruptly (Figure 6). At times this sudden change in outflow, even though it occurs infrequently, can outweigh the advantage of slower changes. Of course this involves the choice of maximum ΔF; the largest should be taken if the limit effect can be undesirable.

Balancing. If abrupt flow changes are to be avoided on start-up or shut-down of units, the averaging type controller must be balanced in manually. This requires certain manipulation which is not necessary on the straight proportional response instrument and, consequently, can necessitate some supervisory assistance to the regular operators at these times.

Higher Cost. Although the additional cost of the reset mechanism is not great, at times it may give some weight to the selection.

There is no exact answer to the question of instrument type although a good practice rule might be that reset should be considered if the value of $\Delta F/Q$ is less than 0.5.

MISCELLANEOUS CONSIDERATIONS

It might be well to point out that the shape of the surge vessel is of no importance; only the available volume between limits is to be considered. Obviously, results would be altered slightly if a horizontal cylindrical vessel were used since the cross section changes with level. However, the slope of the calibration curve of such a vessel varies little between 20 and 80% of the diameter.

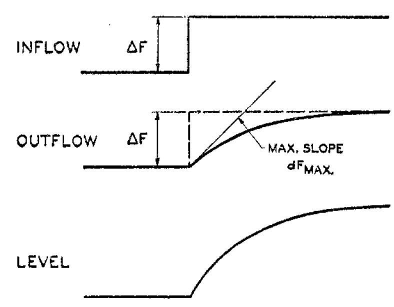


Figure 4. Effect of Flow on Liquid Level for a Proportional Response Controller

The units of flow and capacity used are unimportant so long as they are used consistently; i.e., ΔF may be barrels per minute as long as dF is in barrels per minute per minute, etc. Further, this solution is not limited to outflow control with variable inflow. The control valve could be on the inflow with the outflow uncontrolled.

While the ability of a unit to absorb changes in inflow may vary with throughput, the most general case is probably that the rate of change should be a minimum at all operating rates. This says that so-called characterized valves should be avoided in averaging control; a simple beveled disk valve which gives flow nearly proportional to opening is the best answer, inasmuch as it assures minimum rate of change of flow at large as well as at small throughputs.

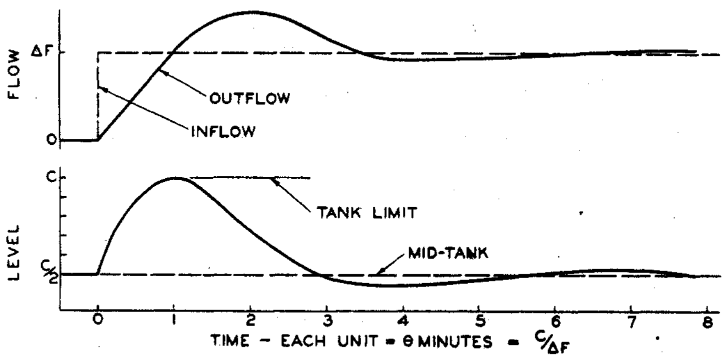


Figure 5. Effect of Reset Response on Liquid Level

Often an averaging level controller does not operate a valve directly but changes the set point of a flow controller on the outflow line. This has the advantage of eliminating the abrupt flow changes which would result if partial plugging of the control valve could occur or if the pressure drop across the valve could change abruptly. The disadvantage to this system is that most flow controllers have nonlinear scales, the flow varying as the square root of the differential. This system, then, in giving linear changes in differential-pressure set point actually causes faster rates of change of flow at low throughputs than at high. In calculating settings from Equations 1 or 4, constant v should be taken as the actual change in the flow set point per lb./sq. in. change in level controller output. Furthermore, the constant should be taken around the point on the flow scale representing maximum expected throughput. If taken at the average flow, the settings would be conservative at low flows, but the upper limit stop could be reached at high flows.

It is apparent that the level measuring device must cover the total allowable level change or more. Similarly, good practice would dictate that a valve positioner be used to eliminate the dead spot caused by valve friction, and a valve positioner with the widest input pressure range should be used to reduce end effects.

One other point can be important when the surge tank is very small compared to the throughput or, better, when ($\theta = C/\Delta F$) is very small. Under these conditions rapid correction in outflow may be required. In this case the lag of level measurement and the lag of operating the valve can become appreciable and affect the control results. It is, then, very important that a level measuring device with small lag be used, such as the direct-float operated instruments or bellows type (aneroid) manometer. In extreme cases it may be necessary to use booster relays to cut valve lag. In general, however, the required rates of valve movement are so slow that valve and measuring lags are not great enough to alter the calculated results appreciably.

EXAMPLES

This paper has attempted to apply numbers to quantities which, admittedly, cannot be evaluated. Even after the maximum rate of change of flow to a unit is calculated, it is still necessary to decide whether or not the unit will successfully absorb this rate of change; that question is not easy to answer. Nevertheless, interjection of Equation 3 into arguments between plant design and operating departments has often cleared away clouds of generalization so well that a common-sense answer is apparent. A typical example is given in problem 1.

Problem 1. A plant has a column with a surge volume in the base of 400 gallons. It is to be put on a service where the maximum sudden change in feed to the column can be of the order of 20 gallons per minute. Normal downflow will be about 100 gallons per minute. Will a level controller be able to absorb this change in flow without upsetting the following column which is to be fed with the bottoms from the first? Or will an expensive high-pressure tank be required to augment the existing capacity?

Solution. From Equation 3 $(dF)_{max}$ will be 1 gallon per minute per minute. Almost any column will be able to accept a 1% per minute change in feed rate. Therefore no auxiliary tank is required.

Problem 2. Flow to a surge tank varies from 30 to 180 gallons per minute. Sudden changes in throughput will not be greater than 50 gallons per minute, and the rate of outflow change regulated by a level controller must not exceed 5 gallons per minute per minute. Pressure drop through the control valve is 25 pounds per square inch. Specific gravity of the liquid is 1.0. Minimum holdup is desirable.

Questions of design, instrumentation, and adjustment must be solved: What must be the tank capacity (*a*) with proportional response controller and (*b*) with proportional plus reset controller (design)? What controller range, valve size, etc., should be selected (instrumentation)? What is the estimate of the controller settings (adjustment)?

Solution. From Equation 1,

$$C = \frac{(\Delta F)(Q)}{(dF)_{max}} = \frac{(50)(180)}{5} = 1800 \text{ gallons}$$

From Equation 3,

$$C = \frac{(\Delta F)^2}{(dF)_{max}} = \frac{(50)^2}{5} = 500 \text{ gallons}$$

The need for minimum holdup indicates that the proportional plus reset instrument should be used. A vertical cylindrical tank, 4 × 6 feet, would hold 500 gallons in 64 out of 72 inches and thus leave 4 inches above and below limit stops.

The nearest standard manometer range above 72 inches is 100 inches of water. A 2-inch, single-seat, beveled-disk diaphragm valve with a capacity of 200 gallons per minute and a valve positioner with an input range of 16 pounds per square inch would be selected.

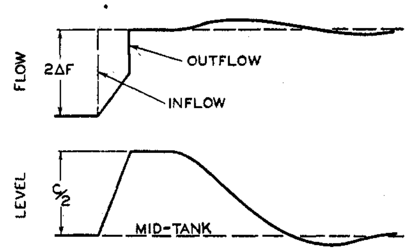


Figure 6. Effect of Limit Stops on Liquid Level

The controller sensitivity can be estimated from Equation 4 after evaluating two constants. Measuring sensitivity m is the pen movement per gallon. The 5-inch controller scale represents 100 inches of water, and 64 inches of water represents 500 gallons; therefore,

$$m = \frac{(64)(5)}{100\ (500)} = 0.0064 \text{ in. of pen movement per gal.}$$

Valve sensitivity v is the flow change per unit change in controller output. Since a linear valve is used, and 16 pounds per square inch change in positioner input makes a flow change of 200 gallons per minute,

$$v = \frac{200}{16} = 12.5 \text{ gal. per min. per lb./sq. in.}$$

The problem gave ΔF as 50 gallons per minute, and C has been determined to be 500 gallons; therefore,

$$S = \frac{\Delta F}{(m)(v)(C)} = \frac{50}{(0.0064)(12.5)(500)} = 1.25 \text{ lb./sq. in. per in.}$$

From Equation 5 the reset rate should be:

$$RR = \frac{(1.5)(\Delta F)}{(C)} = \frac{(1.5)(50)}{500} = 0.15 \text{ per min.}$$

The controller limit stops should be set at 4 and 64 inches of level. Figure 5 shows that after a sudden change in inflow the level will return to mid-tank in a time of about (5) $(C)/(\Delta F)$ or 50 minutes.

SUMMARY OF EQUATIONS

For the proportional response controller,

$$S = \frac{Q}{(m)(v)(C)} \text{ lb./sq. in .per in.}$$

$$(dF)_{max} = \frac{(\Delta F)(Q)}{C} \text{ gal./min./min.}$$

For the proportional plus reset controller,

$$S = \frac{\Delta F}{(m)(v)(C)} = \frac{1}{(m)(v)(\theta)} \text{ lb./sq. in. per in.}$$

$$RR = \frac{1.5(\Delta F)}{(C)} = \frac{1.5}{\theta} \text{ per min.}$$

$$(dF)_{max} = \frac{(\Delta F)^2}{C} = \frac{\Delta F}{\theta}$$

The settings for the proportional plus reset controller can be stated as follows: Sensitivity is set so that a level change equivalent to C moves the valve enough to make a flow change equal to ΔF. Reset rate is set equal to 1.5 divided by the time required to fill the tank at a rate of flow equal to ΔF.

Temperature-Density Relation for Gasoline-Range Hydrocarbons

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The temperature coefficient of density (α) in the equation, $d_4^t = d_4^{20} + \alpha(t - 20)$, for pure hydrocarbons from C_5 to C_{12} is correlated with hydrocarbon structure or type and molecular weight at temperatures near 20° C. by the formula, $-\alpha = m(1/M - 0.002) + 6 \times 10^{-4}$, where M is molecular weight and m is a constant depending only on structural type. This permits an exact conversion of d_4^{20} to A.P.I. gravity whenever the type of compound is known. For application to wider temperature ranges, values of β in the equation, $d_4^t = d_4^{20} + \alpha(t - 20) + \beta(t - 20)^2$, are calculated for the few compounds on which data of sufficient accuracy and range are available. The values of β vary with structure in an unknown manner.

AN ACCURATE temperature-density relation for pure hydrocarbons is needed for conversion of d_4^t to various temperatures and to degrees A.P.I. (60/60° F.). Several correlations of density and of volume with temperature already have been presented. The most general seems to be that of Lipkin and Kurtz (*8*). For the relation,

$$d_4^t = d_4^{20} + \alpha(t - 20) + \beta(t - 20)^2 \quad (1)$$

where d = density, grams/ml.
t = temperature, ° C.

these authors plotted α against molecular weight for various types of hydrocarbons, and β against molecular weight for normal paraffins. A single curve gave a fairly good representation of α for all types of hydrocarbons, although only a fraction of the values fell exactly on the curve.

CORRELATION OF ALPHA

The Lipkin and Kurtz plots show that the shape of the curves is at least approximately hyperbolic. If this is true, a plot of α against the reciprocal of molecular weight will yield a straight line. This was found to be the case, and Figure 1 shows values of α calculated from the most recent and reliable data (enumerated later). Figure 1 shows that divergence from a single straight line is greatest at the lowest molecular weights, that the data tend to converge at higher molecular weights, and that all aromatics fall above the line and all n-paraffins fall below the line; therefore, by differentiating between these types, a more accurate correlation is obtainable. Calingaert *et al.* (*1*) reported obtaining a linear correlation for paraffins on the coordinates of αM *vs.* N, where N is the number of carbon atoms from heptane to eicosane (C_7 to C_{20}). A type form equation linear in αM and N may be transformed algebraically into an equation linear in α and $1/M$ for any given series of hydrocarbons.

Recent data for the individual types were plotted separately with the results shown on Figure 2. The data include n-paraffins from C_5 to C_{16}, isoparaffins through C_9, naphthenes through C_{10}, olefins and aromatics through C_{12}, and a few heavier compounds. On the isoparaffin and olefin plots, points for several isomers of the same molecular weights sometimes superimpose. The data for each individual type are best represented by a straight line. With the exception of isoparaffins, the best lines for all series extrapolate through a hypothetical common point at 500 molecular weight and $\alpha = -60 \times 10^{-5}$. The isoparaffins may also be represented by a line through this common point with less error than occurs between certain isomers of the same molecular weight in other types. Isoparaffins, naphthenes, olefins, diolefins, and acetylenes may all be represented by the same line. A general equation for all types may be written in terms of molecular weight and slope:

$$-\alpha = m(1/M - 0.002) + 60 \times 10^{-5} \quad (2)$$

[1] Present address, University of Michigan, Ann Arbor, Mich.