METHODS AND APPARATUS FOR THE CASTING AND SOLIDIFICATION OF MOLTEN MATERIALS

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The present invention relates to methods and apparatus employed in the casting of molten materials and is particularly described in connection with an embodiment of the invention used for the detection of solidification conditions in centrifugal casting apparatus.

The invention is broadly applicable to any situation where there is a time rate of change of some measurable physical property such as temperature, weight, a dimension, color, velocity or the like, and the time-magnitude curve of the particular property exhibits an irregularity, such as a plateau, signifying the occurrence of some critical phenomenon or indicating that a process has proceeded to a point where a further step is to be performed. As shown hereinafter, a double differentiation method is employed to produce control signals for regulating such steps.

In the particular illustrative embodiment of the invention which is herein disclosed, the solidification point of cooling molten cast iron is ascertained. The freshly poured molten iron cools initially at a changing rate such that the time required for its temperature to drop by a predetermined number of degrees will not exceed a certain predetermined time interval.

When the point is reached where solidification commences, there is a marked decrease in the cooling rate as heat is generated during the exothermic solidification of the iron. At this point, the time interval required for a predetermined drop in temperature becomes much longer than during cooling of the iron in its liquid state. In apparatus employing this invention, the increase in the time interval produces a control effect which causes a slowing down of the centrifugal casting machinery, the advantages whereof are set forth below.

After solidification is complete, the temperature resumes its relatively rapid rate of fall until room temperature is reached. During this time there is no risk whatever of deformation of the casting. The shortened time interval which is again required for the predetermined drop in temperature is caused, in the apparatus of this invention, to produce a control effect which causes the machinery to be stopped completely. As a result, the high speed operation of the casting machinery is discontinued as soon as it is safe to commence operation at reduced speed and the machinery is completely stopped as soon as solidification is complete. Unnecessary wear on the machinery is thus avoided without risking deformation of the casting. Production of cast iron is appreciably increased because the apparatus is operated only as long as necessary, as indicated by the signals derived from the critical points on the cooling curve.

I have further devised a specific embodiment of the invention which has been found to be highly effective in employing the concepts above described. This embodiment comprises a continuously operational temperature measuring element, a self-balancing servosystem which operates to rebalance itself whenever the temperature has changed by an increment of predetermined magnitude, a continuously operating timer having a preset maximum interval, the timer being reset to zero each time that the servosystem rebalances itself, and control means actuated by the timer in response to failure of the servosystem to rebalance itself within the predetermined maximum time interval established by the timer. The utility of this combination will be made apparent hereinafter.

Various objects, features and other advantages of the invention will become apparent upon reading the following specification together with the accompanying drawing forming a part hereof.

Referring to the drawing:

Figure 1 comprises a group of graphs, Figures 1A, 1B and 1C illustrating a cooling curve together with its first and second derivatives;

Figure 2 is a block diagram illustrating the principle of operation of the invention;

Figure 3 is a schematic perspective view illustrating centrifugal casting machinery embodying the invention;

Figure 4 is an electrical circuit diagram of control apparatus used in connection with the casting machinery of Figure 3;

Figure 5 is a group of graphs illustrating certain voltage-time relations in connection with Figure 4;

Figure 5A shows the voltage of an alternating current supply line;

Figure 5B represents the voltage of certain flat-topped waves produced by a vibrator or converter;

Figures 5C and 5D illustrate two voltages which are opposite in phase and which are applied to the anodes of two separate control thyristors; and

Figure 6 shows a modified form of phototube temperature measuring arrangement.

Referring to Figure 1, and particularly Figure 1A, there is shown a cooling curve 10 for cast iron, the temperature at each instant being plotted as an ordinate against time intervals as abscissae. When the molten iron is first poured, it cools at a relatively rapid rate as indicated by the upper portion 11 of the cooling curve 10. After the iron has cooled in a molten condition to point 13, solidification commences. The solidification is an exothermic process and heat is liberated which maintains the temperature fairly constant as indicated by the plateau 14. After solidification is complete, as indicated at point 16, the rapid cooling of the solid casting is resumed as shown by the lower portion 17 of the cooling curve 10.

The first derivative of cooling curve 10 is shown as curve 19 in Figure 1B. During the liquid state, the first derivative exhibits a positive-going negative value as shown by the first portion 20 of curve 19. At the portion 22 of curve 19 which corresponds to the solidification interval, the first derivative rises to zero while the temperature remains constant. Thereafter, the first derivative assumes its negative value as indicated by the terminal portion 23 of curve 19.

Proceeding to the second derivative curve 25, shown in Figure 1C, the portion of curve 25 which corresponds to the rapid rise of the first derivative between portions 20—22 of curve 19 appears as a positive pip 26. On the time scale, this pip is located at the same time as the point 13 of Figure 1A which corresponds to the beginning of solidification. Similarly, when solidification is complete, as at point 16 of Figure 1A, a negative pip 28 appears in the second derivative curve 25. This negative pip 28 is located along the time scale at a time corresponding to point 16 of cooling curve 10.

Figure 2 shows a block diagram of apparatus for deriving the pips 26 and 28 as electrical impulses signifying the beginning and termination of solidification. Because the molten iron radiates energy, its temperature may be evaluated photoelectrically such as by apparatus to be
hereinafter described. Accordingly, a lens 29 focuses an image of a body of molten iron 31 on a phototube 32. The phototube 32 comprises an anode 34 and cathode 35. The anode-cathode circuit of phototube 32 is energized from a suitable source of anode potential through a resistor 37. The higher the temperature of the molten iron 31, the greater will be the electron emission from cathode 35 and, because of the voltage drop across resistor 37, the less will be the potential drop between anode 34 and cathode 35 of the phototube 32. As the molten iron 31 cools, the potential across phototube 32 will increase correspondingly. The time-voltage curve across phototube 32 is therefore of effectively the same shape as the time-temperature or cooling curve 10 of Figure 1A but is inverted or opposite in sense with respect to the cooling curve 10.

The potential drop across phototube 32 is applied to the input terminals 38 of a first differentiator circuit 40. Differentiator 40 may be of conventional arrangement using resistor-capacitor networks, or the like. As noted above, the input at terminals 38 will have the shape of curve 10 shown in Figure 1A, although opposite in sense. The electrical output at output terminals 41 of differentiator 40 is arranged by means including phase inversion, if required, to have the time magnitude characteristics shown by the first derivative curve 19 in Figure 1B. This electrical output is applied to the input terminals 43 of a second differentiator 44. The output of second differentiator 44 is arranged to have the characteristics illustrated in Figure 1C including the positive and negative pips 26 and 28, respectively. This output is connected to two polarity responsive trigger circuits 46 and 47. The trigger circuit 46 responds only to the positive pip 26 and the trigger circuit 47 responds only to the negative pip 28. Trigger circuits of this character are conventional and may include relays, gas-filled tubes, or the like.

When dealing with molten iron which is cooling in centrifugal casting machinery, it is desirable to keep the mold1 spinning at high speed until solidification commences. During solidification, the centrifugal speed may be materially reduced with a significant saving in wear on the machinery. After solidification is complete, the machinery may be stopped entirely and the solidified casting permitted to cool to room temperature with the mold stationary. Accordingly, trigger circuit 46 may be used to initiate the reduced speed interval and trigger circuit 47 may operate to stop the machinery completely. When this is attempted to be done by an operator, there is danger of slowing or stopping the machinery prematurely so that the partially solidified casting collapses. To be on the safe side, it is customary for the operator to run the machinery at high speed for a longer period of time than is strictly necessary and the wear on the machinery is thereby needlessly increased. The control system of Figure 2 therefore presents unusual advantages in terms of reduced maintenance expense and the avoidance of collapses of partially solidified castings.

The arrangement of Figures 2 has some practical operating disadvantages since some difficulty is likely to be encountered because of the long time base of the cooling curve which may extend over a period of many minutes. Capacitor-resistor differentiating networks for dealing with such long time intervals become objectionable from a practical or commercial viewpoint. Accordingly, it becomes desirable to utilize apparatus such as shown in Figures 3 and 4 in practicing the invention. Instead of infinitesimal time and temperature intervals which prevail in a differentiating circuit, discrete increments are used as a practical means for obtaining control signals from the visual points of the actual cooling curve.

Referring to Figure 3, there is shown an elongated rotating flask or mold 49 adapted for producing cast iron pipes. The flask 49 is provided with longitudinally spaced supporting rings 50. The rings 50 engage drive wheels 52 which are fixed to a shaft 53. The shaft 53 is coupled to a drive motor 55 for spinning the flask 49 on its longitudinal axis. Electrical power for the operation of motor 55 is supplied from a suitable source (not shown) through a conventional motor controller 56 which includes control circuits for starting and stopping the motor 55 and also for running the motor 55 at reduced speed. The specific construction of controller 56 will depend upon the size of the motor and the type of electric power which is available, and any suitable conventional controller may be selected. Additional control apparatus, described in greater detail below, is disposed in a main console or cabinet 58.

The flask 49 is provided at one end with a filling aperture not visible in the drawing. A funnel 59 extends through the filling aperture and communicates with the interior of the flask 49. When it is desired to pour molten iron into a new pipe into the flask 49, the iron is poured from a ladle 61 into the funnel 59 through which it flows into the interior of flask 49. The other end of flask 49 is closed by a cover which has a peep hole 64 formed at its center.

A phototube pickup in the form of a camera unit 65 is focused on the molten iron through the peep hole 64 for observation of the temperature within the flask 49. The camera unit 65 comprises an optical system (Figure 4) diagrammatically indicated as a lens 67 arranged to focus an image of the peep hole 64 on the surface of a phototube 68 comprising a photo-sensitive cathode 70 which is shown connected to ground. The phototube 68 is also provided with an anode 71 which is connected to a source of anode current through a resistor 73. As explained above in connection with Figure 2, the potential at anode 71 will become increasingly positive as the temperature within flask 49 drops. Alternately the phototube 68 may be of the lead sulfide type.

Anode 71 is shown connected to a lower stationary contact 74 of a vibrator or converter unit 76. The lower contact 77 of vibrator 76 is connected to the movable contact 79 of a servomotor-operated potentiometer 80. The vibrator 76 is provided with a vibrating contact arm 82 which is vibrated at line frequency by an electromagnetic operating winding 83 connected to a source of alternating current designated "A.C."

The potentiometer 80 is connected to deliver an adjustable direct current reference potential from movable contact 79 to the stationary contact 77 of vibrator 76. Accordingly, if the potential on anode 71 is equal to the potential on movable potentiometer contact 79, no alternating current potential will appear on vibrating contact arm 82. If, however, there is a potential difference between the vibrator stationary contacts 74 and 77, an alternating potential of flat-topped wave shape will appear on vibrating contact arm 82 and the phase of this potential will be determined by the polarity of the difference potential, if any, between the stationary contacts 74 and 77 of vibrator 76. This flat-topped wave is shown in Figure 3B. As described in greater detail below, the phase of the flat-topped wave is considered from the aspect of its polarity or a phase difference of 180 degrees with respect to the alternating current supply. The peak amplitude of this alternating difference potential of flat-topped wave shape which appears on the vibrator contact arm 82, it being assumed for purposes of illustration that the vibrator arm is in movement about 3% of the time and in steady engagement with one or the other of the stationary contacts 74 or 77, at the latter time will be substantially proportional to the magnitude of the direct current difference potential between stationary contacts 74 and 77. The potential on vibrating contact arm 82 is applied through a coupling capacitor 85 to the input of an alternating current amplifier 86.

The output of alternating current amplifier 86 is applied to control a pair of gas-filled triodes 88 and 89 and it is also applied to the input of a power amplifier 91 for the operation of a servomotor 92 comprising a rotor 93, the
servomotor 92 being under control of a pair of normally open contacts 94 of a timer reset and servomotor control contactor 95.

The servomotor 92, as shown, is of the two-phase alternating-current type with one of its phases 92a connected to be continuously energized from the A. C. supply as indicated and the other phase 92b connected for energization from the output of power amplifier 91 whenever contacts 94 are closed. The speed and direction of rotation of servomotor 92 will be determined by the magnitude and direction of the direct current potential difference between the stationary contacts 74 and 77 of vibrator 76. The rotor 93 of servomotor 92 is mechanically connected as indicated by the dashed line 97 to drive the movable contact 79 of potentiometer 80 to reduce this difference voltage to zero.

The temperature rise triode 88 comprises a grounded cathode 98, a control grid 100 and an anode 101. The anode 101 is connected for energization from the upper half 103 of the center-tapped secondary winding 104 of a transformer 106 through the operating winding 107 of a temperature rise contactor 109. A suitable source of biasing voltage 110 is connected to control grid 100 through a grid resistor 112. The control grid 100 is connected through a biasing resistor 115 to the output of A. C. amplifier 86. The triode 88 is thus prevented from firing unless a positive peak voltage of sufficient magnitude from the output of A. C. amplifier 86 reaches grid 100 in phase with a positive potential at anode 101 from transformer secondary winding 104. Thus, until the unbalance voltage between vibrator contacts 74 and 77 is of sufficient magnitude and of the correct polarity, triode 88 will remain in an unbiased condition. These polarities are so selected that triode 88 fires only in response to an increase in temperature, as hereinafter described in greater detail.

The temperature drop triode 89 is provided with a grounded cathode 115, a control grid 116 and an anode 118. The anode 118 is connected through the operating winding 119 of a temperature drop contactor 121 to the lower half 122 of center-tapped secondary winding 104. The grid 116 is connected through a coupling capacitor 124 to the output of the A. C. amplifier 86 and grid 116 is connected to a suitable source of biasing voltage 111 through a grid resistor 127. Since their anodes are energized by oppositely poled halves of center-tapped secondary winding 104, the triodes 88 and 89 are phase sensitive and one or the other will fire depending upon the polarity of the direct current unbalance potential between vibrator contacts 74 and 77. As shown in Figure 5, the line voltage A. C. indicated by Figure 5A operates the vibrator 76 to produce a flat-topped wave as illustrated in Figure 5B. The phase of this flat-topped wave will be either as indicated by the full line or by the dotted line, depending upon the polarity of the direct current potential difference between the stationary contacts 74 and 77 of vibrator 76. Its amplitude will, of course, depend upon the magnitude of such potential difference. As shown in Figure 5B, this flat-topped wave is represented diagrammatically and substantially as it appears at the input of the amplifier 86. The anode voltage from the upper half 103 of transformer secondary winding 104 is shown in Figure 5C and is applied to the temperature rise thyatron 88. The positive-going portions of Figure 5C are in phase with the full line curve of Figure 5B and the full line curve of Figure 5B therefore represents the phase of the flat-topped wave which accompanies a temperature rise. The voltage of the lower half 122 of transformer secondary winding 104 is represented in Figure 5D. The positive-going portions of the sinusoidal voltage wave illustrated in Figure 5D are substantially or effectively in phase with the dotted line flat-topped wave of Figure 5B. Thus, the relative phasing of the flat-topped wave which accompanies a temperature drop is shown by the dotted line flat-topped wave of Figure 5B. In Figures 5C and 5D, the negative-going portions of the sinusoidal waves are shown by dotted lines since these negative-going portions are ineffective to fire either triode 88 or 89, respectively.

The temperature drop contactor 121 comprises two sets of normally open contacts designated 128 and 129. Each time that the temperature drop thyatron 89 is fired by a sufficient increase of the amplitude of the dotted line wave of Figure 5B, contacts 129 close and energize the operating winding 130 of the servomotor control contactor 95. This, in turn, causes closure of the contacts 94 which connect the winding 92b of servomotor 92 to the output of the power amplifier 91. Energization of servomotor winding 92b causes rotor 93 to adjust the movable contact 79 of potentiometer 80 to a balance point at which the amplitude of the flat-topped wave of Figure 5B is made substantially equal to zero. Accordingly, the temperature drop thyatron 89 will thereafter cease firing, releasing both the temperature drop contactor 121 and the servomotor control contactor 130, whereupon servomotor control contacts 94 open. The opening of contacts 94 disconnects the winding 92b of servomotor 92 from the output of the power amplifier 91, leaving the potentiometer 80 adjusted to a position of balance such that the control grid 100 has greatly reduced or zero direct current input and the control grid 116 of temperature drop thyatron 89 likewise receives a greatly reduced or substantially zero grid voltage. This substantially zero grid voltage is insufficient to fire either of the thyatrons 88 or 89 and this zero voltage is obtained each time that the winding 92b of servomotor 92 is energized, the balance being produced by an accompanying adjustment of the potentiometer 80 which is mechanically connected to the rotor 93.

Servomotor control contactor 95 is also provided with a pair of normally open contacts 131 which are connected to a continuously operating resettable timer 133. The timer 133 may be motor driven, or it may comprise a condenser discharge circuit, a dashpot or other conventional timing means. In any event, each time that contacts 131 close, the timer 133 is reset to zero. If the preset time interval for which timer 133 is adjusted expires without any closure of timer reset contacts 131, then the timer 133 will close its normally open contacts 134 and 136. The contacts 136 of timer 133 energize the servomotor control contactor 95 in the same manner as the contacts 129 of temperature drop contactor 121. This is described in greater detail below.

The operating winding 137 of a slowdown contactor 139 is controlled by the contacts 134 of timer 133. The slowdown contactor 139 is provided with locking contacts 140 and control contacts 142. The control contacts 142 are connected with conventional motor control circuits (not shown) within the motor controller 56 to operate the drive motor 55 at reduced speed when the control contacts 142 are closed. The slowdown contactor 139, when operated, sets up an energizing circuit for the operating winding 143 of a stop contactor 145. This energizing circuit includes contacts 128 of the temperature drop contactor 121 and locking contacts 140 of the slowdown contactor 139.

The stop contactor 145 comprises locking contacts 148 and control contacts 149. The locking contacts 148 are included in a common locking circuit along with the locking contacts 140 of the slowdown contactor 139. This common locking circuit includes a set of normally closed contacts 150 which are a part of the temperature rise contactor 109. The temperature rise contactor 109 also comprises normally open contacts 151 for energizing the servomotor control contactor 95 are described below. The control contacts 149 of the stop contactor are connected with conventional motor control circuits (not shown) within the motor controller 56 whereby the drive motor 55 is completely stopped when the control contacts 149 are closed. The actual physical location of the slow-
down and stop contactors 139 and 145, respectively, may be either within the motor controller 56 or in the main console 58, according to convenience, and are illustratively indicated by the dotted line in Figure 4 as being within the motor controller 56.

In operation, a new charge of molten iron is poured into the flask 49 from the ladle 61 through the funnel 59, the drive motor 55 then being stopped. Unless this is the first operation, the slowdown and stop contactors 139 and 145 will both be locked in from the preceding operation, as will appear more fully below. After the metal has been poured, drive motor 55 is operated at high speed to spin the flask 49. The camera unit 65 observes an increase in temperature through the peep hole 64 as the molten metal is poured. The accompanying response of the phototube 66 creates a large unbalance in potential between the fixed contacts 74 and 77 of vibrator 76, the direction or polarity of the unbalance being in the temperature rise direction as represented by the flat-topped wave shown in full lines in Figure 5B. This full-line flat-topped wave causes the temperature rise thyristor 88 to fire and thereby energize the operating winding 107 of the temperature rise contactor 109. This causes the normally closed contacts 150 of the temperature rise contactor 109 to thereby unlatch the slow-down contactor and stop contactors 139 and 145, respectively, if they were previously locked in. In the case of the first casting operation of a series, the stop and slowdown contactors 139 and 145 will have been previously unlocked when the power was shut off after completion of the preceding series of casting operations.

Temperature rise contactor 109 also closes its normally open contacts 151 thereby energizing the servomotor control relay 95, and thus causing the servomotor 92 to re-balance the potentiometer 80. This balancing of potentiometer 89 reduces the flat-topped wave voltage to zero, whereby the temperature rise thyristor 88 stops firing. During this period of rising temperature, the grid voltage on the temperature drop thyristor 89 is either out of phase with its anode voltage or is made negligible by the balancing of potentiometer 80. The temperature rise ceases as soon as the molten iron has been poured and immediately thereafter the temperature commences to drop in the manner indicated in Figure 1A by the steep initial portion 11 of the cooling curve 10.

As the temperature drops relatively rapidly during portion 11 of the cooling curve 10, temperature drop thyristor 89 fires before the timer 133 can close its contacts 124 to lock in the slowdown contactor 139. Each time that the temperature drop thyristor 89 fires, it energizes the temperature drop contactor 121 and closure of contacts 129 of the temperature drop contactor 121 operates the servomotor control contactor 95. Operation of the servomotor control contactor 95 connects the amplifier 91 to servomotor winding 92b causing the servomotor 92 to re-balance the potentiometer 80. Operation of the servomotor control contactor 95 also closes contacts 131 which recycle the timer 133. Thus, during the initial portion 11 of the cooling curve 10, the temperature drop contactor 89 fires repeatedly, the time interval between successive firings being too short for timer 133 to close its contacts 134. It is not until the solidification temperature is reached and solidification commences, as indicated at 13 on the cooling curve 19 of Figure 1A, that the cooling rate becomes reduced, this reduced cooling rate being indicated at 14. Commencing at the critical point 13, solidification is in progress and the relatively slow cooling rate indicated by the plateau 14 is in effect. As soon as the solidification point 13 is reached, the predetermined amount of temperature drop which is required to fire the triode 59 will fail to occur within the preset time interval of timer 133. When this situation occurs, it will be safe to slow down the flask 49 in order to reduce wear on the moving parts.

When the timer 133 first closes its contacts 134, the operating winding 137 of slowdown contactor 139 is energized and contactor 139 locks in under control of the closed contacts 130 of the temperature rise contactor 109. Contacts 136 of timer 133 also close, thereby energizing the operating winding 130 of the servomotor control contactor 95. Operation of the servomotor control contactor 95 recycles the timer 133 and also re-balances the potentiometer 80. Because the rate of temperature drop is quite slow during the solidification interval, as indicated by the plateau 14 of cooling curve 10, the amount of adjustment required to re-balance the potentiometer 80 will be comparatively small and a short interval of energization of the servomotor winding 92b will be sufficient. During the solidification interval, the drive motor 55 will operate at reduced speed sufficient to prevent collapse of the partially solidified casting and the timer 133 will repeatedly recycle itself by closure of its contacts 136 and operation of servomotor control contactor 95 without any firing of the temperature drop thyristor 89 or operation of the temperature drop contactor 121. The temperature drop thyristor 89 does not fire because the potentiometer 80 is repeatedly re-balanced by operation of the timer contacts 136 and during the solidification interval represented by the plateau 14 of cooling curve 10, the temperature drop thyristor 89 is insufficient to fire the temperature drop thyristor 89.

When solidification has been completed, however, and the critical point 16 of cooling curve 10 has been reached, the temperature again begins to fall relatively fast as the solidified casting cools to room temperature. It is then safe to stop the drive motor 55 completely without any danger of collapse of the fully solidified casting. The terminal portion 17 of the cooling curve 10 is again steep like the initial portion 11. Accordingly, the temperature drop thyristor 89 fires before the time interval of timer 133 expires and the temperature drop contactor 121 operates with the slowdown contactor 139 already operated. The closure of contacts 128 of temperature drop contactor 121 energizes the operating winding 143 of the stop contactor 145 causing the stop contactor 145 to operate and lock in through its locking contacts 148. Its control contacts 146 then close, thus stopping the further running of the drive motor 55 until the next casting operation is commenced.

Figure 6 shows a modified form of phototube arrangement for use in the camera unit 65. Because the location of peep hole 64 may vary for different sizes of the flask 49, the optical system comprises a revolving scanning mirror 152 interposed between the lens 67 and phototube 68. The revolving mirror 152 is driven at constant speed by a small motor or other suitable means (not shown). The mirror 152 thus produces a vertical scanning of the field in which peep hole 64 may be located.

The phototube produces a positive potential across a resistor 154 which decreases as the temperature decreases. The resistor 154 is connected through the grid of a triode 155. The triode 155 is associated with a capacitor 157 and a cathode resistor 158 which are so selected that triode 155 operates as a peak measuring device. As a result, the potential on conductor 160 will vary in accordance with the peak temperature observed during the course of each scanning operation. The conductor 160 is connected to the vibrator contact 74 as in Figure 4. However, because the circuit is such that the potential on conductor 160 becomes decreasingly positive with decreasing temperature, the polarity of transformer 106 must be reversed so that the triodes 58 and 59 will fire correctly.

While I have shown what I believe to be the best embodiments of my invention, it will be apparent to those skilled in the art that many modifications may be made therein within the spirit and scope of the invention as defined in the appended claims.
What is claimed is:
1. The method of producing centrifugal castings which comprises the steps of introducing the casting material in fluid electrical potential, spinning said mold, continuously measuring the temperature of said fluid material, generating a changing electrical potential of instantaneous magnitude corresponding to said temperature, and reducing the spinning speed of said mold in response to a change in the time rate of change of said temperature as determined by a corresponding change in the time rate of change of said electrical potential.

2. The method according to claim 1, comprising the further step of stopping the spinning of said mold in response to a further change in said time rate of change of said temperature.

3. The method according to claim 1, wherein said casting material is molten metal which radiates energy during the course of its cooling, said temperature measuring step being performed by measurement of the intensity of said radiation.

4. The method of producing centrifugal castings which comprises the steps of introducing the casting material in molten form into a mold, spinning said mold, continuously measuring the radiation energy from said material during the course of its cooling, generating an electrical potential from said radiant energy, said potential when plotted against time as a base producing a curve having a marked change in the magnitude of its second derivative at the time when said material starts to solidify, and reducing the spinning speed of said mold in response to said generated electrical potential at said time of said marked change in said second derivative.

5. The method of controlling an apparatus responsive to a control-signal which is in timed relationship to a critical point in the time-magnitude characteristic of a changing physical quantity, said method comprising the steps of continuously measuring said quantity to determine the magnitude thereof, generating a changing electrical potential of instantaneous magnitude corresponding to said first-named magnitude, balancing said potential against an adjustable reference potential whereby a change in said first-named magnitude produces an unbalance, readjusting said reference potential to restore said balance whenever said unbalance exceeds a predetermined maximum value, whereby the restoration of said balance is repeated at a repetition rate corresponding to the first derivative of said time-magnitude characteristic, producing a control signal when the time interval between successive restorations of said balance deviates from uniformity by a predetermined maximum deviation interval and applying said control signal to said apparatus.

6. Apparatus of the character described, comprising in combination continuously operative measuring means for determining the magnitude of a measurable physical property, first differentiating means connected to said measuring means for obtaining the first derivative of the time-magnitude curve of said property, second differentiating means connected to said first differentiating means for obtaining the second derivative of said time-magnitude curve, and control means connected to said second differentiating means for response to an irregularity in the instantaneous slope of said time-magnitude curve.

7. Apparatus of the character described, comprising in combination continuously operative measuring means for determining the magnitude of a measurable physical property which varies continuously in a predetermined direction, the rate of said variation being characterized by a discontinuity which signifies the attainment of a critical condition, a first control means connected to said measuring means and having a threshold such that said control means is responsive to a discrete incremental change in said measured magnitude which is of a predetermined minimum value, timing means connected to said first control means, said timing means being responsive to failure of said discrete incremental change to occur within a predetermined maximum time, and a second control means operated by said timing means in response to such failure.

8. Apparatus according to claim 7, further comprising an adjustable reference, said first control means being connected to said measuring means and to said reference for response to a discrete unbalance therebetween, and rebalancing means actuated by said first control means and connected to adjust said reference for reestablishing a balance in response to operation of said first control means.

9. Apparatus of the class described, comprising in combination continuously operative measuring means for deriving a unidirectional control potential of a magnitude which is determined by the magnitude of a physical property measured by said measuring means, adjustable potentiometer means for deriving a unidirectional reference potential, comparator means connected to said measuring means and to said potentiometer means, said comparator means being responsive to an unbalance between said control and reference potentials which is of predetermined magnitude, balancing means controlled by said comparator means and connected to said potentiometer means to adjust said reference potential for establishing a balance between said control and reference potentials, timing means controlled by said comparator means and responsive to failure of said comparator means to respond to an unbalance within a predetermined maximum time interval, and control means actuated by said timing means in response to such failure.

10. Apparatus according to claim 9, wherein said comparator means comprises vibrating contact means operating at the line frequency of an alternating current supply circuit, an alternating current amplifier having its input connected by said vibrating contact means alternately to said measuring means and to said potentiometer means for deriving therefrom an alternating potential of phase and magnitude which varies in accordance with the direction and magnitude of said unbalance, and phase sensitive means connected to the output of said amplifier and operated from said supply circuit, said phase sensitive means having a threshold for response only when said unbalance is at least of said predetermined minimum magnitude.

11. Apparatus according to claim 10, in which said phase sensitive means comprises at least one gas discharge tube energized by said supply circuit in predetermined phase for response to a predetermined polarity of said unbalance.

12. Apparatus according to claim 10, wherein said phase sensitive means comprises contactor means actuated in response to said minimum unbalance, and in which said balancing means includes servomotor means for adjusting said potentiometer means, said servomotor means being connected to the output of said amplifier by actuation of said contactor means.

13. In combination with a rotatable mold, means for introducing molten material into said mold for solidification therein, and drive means for spinning said mold during said solidification, the provision of radiation responsive means arranged to receive radiant energy from said molten material and derive a control potential therefrom in accordance with the magnitude of said energy and the corresponding temperature of said material, adjustable reference potential means for deriving a reference potential equal and opposite to said control potential, comparator means connected to said radiation responsive means and to said reference potential means for determining an unbalance of predetermined minimum magnitude between said control and reference potentials, balancing means controlled by said comparator means and connected to said potentiometer means to adjust said reference potential for establishing a balance between said control and reference potentials, timing means controlled
by said comparator means and responsive to failure of said comparator means to respond to an unbalance within a predetermined maximum time interval, and control means actuated by said timing means in response to such failure, said control means causing a reduction in the speed of operation of said drive means.

14. Apparatus according to claim 13 wherein said control potential is a unidirectional potential, in which said reference potential means comprises adjustable potentiometer means for obtaining a unidirectional reference potential, and wherein said comparator means comprises vibrating contact means operating at the line frequency of an alternating current supply circuit, an alternating current amplifier having its input connected by said vibrating contact means alternately to said measuring means and to said potentiometer means for deriving therefrom an alternating potential of phase and magnitude which varies in accordance with the direction and magnitude of said unbalance, and phase sensitive means connected to the output of said amplifier and operated from said supply circuit said phase sensitive means having a threshold for response only when said unbalance is at least of said predetermined minimum magnitude.

15. Apparatus according to claim 14, in which said phase sensitive means comprises at least one gas discharge tube energized by said supply circuit in predetermined phase for response to a predetermined polarity of said unbalance.

16. Apparatus according to claim 14, wherein said phase sensitive means comprises contactor means actuated in response to said minimum unbalance, and in which said balancing means includes servomotor means for adjusting said potentiometer means, said servomotor means being connected to the output of said amplifier by actuation of said contactor means.

17. The method of producing centrifugal castings which comprises the steps of introducing the casting material in molten form into a mold, spinning said mold, allowing said material to solidify by cooling in said spinning mold, continuously measuring the radiation of energy from said cooling material, deriving an electrical potential of instantaneous magnitude corresponding to said measured radiant energy, said potential when plotted against time as a base being a cooling curve having a shape such that its second derivative exhibits separate pips of opposite polarities at the beginning and at the end, respectively, of the period of solidification of said material, slowing down the spinning of said mold upon the occurrence of the first of said pips, and stopping the spinning of said mold upon the occurrence of the second of said pips.

18. The method of controlling an apparatus according to
the solidification of a cooling liquid, said method comprising the steps of continuously measuring the temperature of said liquid, generating a changing electrical potential of instantaneous magnitude corresponding to said temperature, producing a control signal in response to a change in the time rate of change of said temperature as determined by a corresponding change in the time rate of change of said electrical potential, and applying said control signal to said apparatus.

19. The method of controlling an apparatus responsive to a control signal, said method comprising the steps of continuously measuring a changing characteristic of a body, generating a changing electrical potential of instantaneous magnitude corresponding to said changing characteristic, producing a control signal in response to a change in the time rate of change of said characteristic as determined by a corresponding change in the time rate of change of said electrical potential, and applying said control signal to said apparatus.

20. An apparatus of the class described, comprising in combination continuously operative measuring means for deriving a control potential of a magnitude which is determined by the magnitude of a physical property measured by said measuring means, adjustable means for deriving a reference potential, comparator means connected to said measuring means and to said adjustable means, said comparator means being responsive to an unbalance between said control and reference potentials which is of predetermined minimum magnitude, balancing means controlled by said comparator means and connected to said adjustable means to adjust said reference potential for establishing a balance between said control and reference potentials, timing means controlled by said comparator means and responsive to failure of said comparator means to respond to an unbalance within a predetermined maximum time interval, and control means actuated by said timing means in response to such failure.

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