Design of Bovine SemenTemperature ControllerUsing PID

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Abstract

Development of better bovine's assisted reproduction device in livestock industry requires a temperature controller to help researcher choosing best bovine's spermatozoa. This study aims to design bovine's semen temperature controller prototype which fully controlled using PID (Proportional Integral Derivative) algorithm. Temperature target is achieved using combination between peltier module's polarity switching and PWM (Pulse-Width Modulation)regulation due to itsreal-time error status. Testing result shows bovine's semen temperature controller prototype were able to achieve linear response ranging from $-5^o C$ to$50^o C$with maximumcooling rate $-0{,}9^o C/second$ and maximumheating rate$1{,}7^o C/second$.

Keywords:temperature controller, bovine's semen, assisted reproduction, PID, PWM, peltier module, temperature stage**.**

1. Introduction

Development of better bovine's assisted reproduction device in livestock industry requires a supporting devicewhich can helpresearcher to produce high-quality bovine calf. Technical constraintdue to achieve better procedure finding best spermatozoa from leading maleis important issue in high-quality bovine's calf production. This study aimfindinga new method to assist researcher choosing best bovine's spermatozoa through sperm motility decrement using semen coolingmethod. By decreasing bovine's sperm motility,we expect professional observers can get better visualization when tryto recognizingbest bovine's spermatozoa.

2. Theoretical Basis

2.1. Peltier-Seebeck effect

Peltiereffectis a phenomenonof heat exchange atthermocouple contact area in closed electricity circuit whena pair type of thermocouple is electrified in one direction. Discovery of peltiereffect was publishedin 1834byFrenchphysicistnamedJ.C.A.Peltier, thirteen years after invention ofthermoelectric effectbyT.J.Seebeck. Both peltier and seebeck effects, they are often considered comes froman identicalphysicalprocess[1].

Figure 1 Peltier module(source: *www.tetech.com*)

Theoryabout peltierandseebeckeffectsare basedon resultant analysis ofelectromotiveforcederivedfrom electron concentration gradient in used thermocouple materials. The theoryassumesif electronsconcentrationis associated withthermal gradientthat occurs when a series ofthermocoupleis givendirect-currentelectricitycontinuously.Refer to seebeckequation in [1];electromotiveforcedifferences (ΔU) which measuredat thermocouplecontact area are given by (1)

$$\Delta U = \int_{T_1}^{T_2} (S_A(T) - S_B(T))\, dT \qquad (1)$$

where

$$S(T) = \varepsilon_0 \frac{T}{\theta_v + T} \qquad (2)$$

and

$$\varepsilon_0 = \frac{k_B}{e} = 86{,}17\ \mu V K^{-1} \qquad (3)$$

T_1 and T_2 are temperature measured at thermocouplecontact area, S is seebeckcoefficientwhich dependson type ofthermocouple material used, θ_v is thermocouple characteristictemperature, k_B is Boltzmann's constantand e iselementary charge.Refer to[1]; rate of heatinterchange atthermocouple contact areais proportional to amount of electrical current. This phenomena canwritten as (4)

$$\frac{dQ}{dt} = \pi \frac{dq}{dt} \qquad (4)$$

with

$$\pi = \frac{dQ}{dq} \qquad (5)$$

where π is Peltier coeffisient, Q isheatabsorbedorreleasedatthermocouple contact area and q is amount of electrical chargeflowingthrough closed circuit. According to Thomson, peltiercoefficientis dependent to temperature andcan be rewritten as (6)

$$\pi(T) = S(T)\, T \qquad (6)$$

And if(6) is substitutedwith(2), itwill result final peltier's equation (7)

$$\pi(T) = \varepsilon_0 \frac{T^2}{\theta_v + T} \qquad (7)$$

2.2. PID control

PIDcontrolis acontrol algorithmwhich combinesproportional, integralandderivativecontrollers. Refer to [2][3], PIDcontrolalgorithm can be shown as(8)

$$V_0 = K_p e + K_i \int_{t_0}^{t} e\, dt + K_d \frac{de}{dt} \qquad (8)$$

with V_0 iscontrolleroutputsignal, e is input error signal, t is time, K_p is proportional constant, K_i is integral constantand K_d is derivative constant.Equation(8)represents PIDcontrolin continuoustime domain. If(8)will be appliedindiscretedomain system thenPID continuous timedomainequation must be changed into PIDdiscretetime domain. By deriving(8) we can obtain (9)

$$\frac{dV_0}{dt} = K_p \frac{de}{dt} + K_i e + K_d \frac{d}{dt}\left(\frac{de}{dt}\right) \qquad (9)$$

Subsequently, if dt is substitutedusing shorttime interval(Δt) of T then(9)will change into(10)

$$\frac{\Delta V_0}{T} = K_p \frac{\Delta e}{T} + K_i e + K_d \frac{\Delta}{T}\left(\frac{\Delta e}{T}\right) \qquad (10)$$

or,

$$\Delta V_0 = K_p \Delta e + K_i e T + K_d \Delta \left(\frac{\Delta e}{T}\right) \qquad (11)$$

based on the definition,

$$\Delta V_0 = V_{on} - V_{on-1} \qquad (12)$$

$$\Delta e = e_n - e_{n-1} \qquad (13)$$

so (11)can be rewritten as(14)

$$V_{on} - V_{on-1} = K_p(e_n - e_{n-1}) + K_i eT + \frac{K_d}{T}(\Delta e_n - \Delta e_{n-1}) \qquad (14)$$

and if defined

$$\Delta e_n = e_n - e_{n-1} \qquad (15)$$

$$\Delta e_{n-1} = e_{n-1} - e_{n-2} \qquad (16)$$

Then bysubstituting(15) and(16) into (14), we can get final PID equation shown in (17)

$$V_{on} = V_{on-1} + K_p(e_n - e_{n-1}) + K_i e_n T + \frac{K_d}{T}(e_n - 2e_{n-1} + e_{n-2}) \qquad (17)$$

Equation (17) represents PID control equation in discrete time domain and readyto implement intoanydigital controller.

2.3. Pulse-Width Modulation (PWM)

PWMis a methodto control electrical powertransmitted into any electrical loadin electronic system usingmanipulated pulse-activation period [4]. Power intensity control was performed byregulating pulse train signal togetdirect-current voltageequivalencies[5] [6]and can be expressed mathematically as(18)

$$\overline{V_{DC}} = \frac{1}{T}\int_0^T V(t)\,dt \qquad (18)$$

where $\overline{V_{DC}}$ isPWM's output direct-current voltageequivalencies, $T$is working period of PWM's signal activation and $V(t)$ is PWM power supplyvoltagefunction.InPWMmethod, transmitted powerequivalency isperformedthrough manipulated signal activationperiod calledduty cycle(D) [4]. $V(t)$has $V_{DC\ max}$ for $0 < t < DT$and $V_{DC\ min}$ for $DT < t < T$.D ranging from 0% to 100%. Mathematically, PWM's voltage equivalenciescan be declared in (19)

$$\overline{V_{DC}} = \frac{1}{T}\left(\int_0^{DT} V_{DC\ max}\,dt + \int_{DT}^{T} V_{DC\ min}\,dt\right) \qquad (19)$$

because$V_{DC\ max}$ and $V_{DC\ min}$ are constants which independent by time, equation (19) can be changed into (20)

$$\overline{V_{DC}} = \frac{DT\,V_{DC\ max} + (1-D)T V_{DC\ min}}{T} \qquad (20)$$

and can be rewritten as (21)

$$\overline{V_{DC}} = D V_{DC\ max} + (1-D) V_{DC\ min} \qquad (21)$$

From(21)it can be seen if $D$is determining parameterwhich can regulate $\overline{V_{DC}}$ directly. If(21)will be appliedto controllinginjected power to an electronic load, it can be simplychanged D-value to generate direct-currentoutput voltage equivalencies.

2.4. ATMEGA 8 microcontroller

Microcontrolleris electronic devices which can be programmed to execute specific application routine. Physically, microcontroller is an integrated circuit consists of processor, RAM (Random Access Memory), permanent memory and input/output pin which can be programmed to communicate with external electronic devices.

Figure2 ATMEGA 8microcontroller [7]

Figure2 shows physical appearance of ATMEGA 8 microcontroller. Refer to [7]; ATMEGA 8 is an 8-bit microcontroller produced by ATMEL Corp. comes with 8 Kbyte Flash PEROM (Programmable and Erasable Read Only Memory) to store main program code. ATMEGA 8 can work up to 16 MHz clock frequencies. ATMEGA 8 main processor is designed using RISC processor architecture (Reduced Instruction-Set of Computing) named ATMEL AVR®.

3. Temperature Controller Devices Construction

Bovine'ssementemperature controller device is consistedof software andhardware parts which connected eachother through serialcommunication. Software constructionconsists of GUI (Graphical UserInterface)to handle process interaction with user and make set pointinput, moving average block is used to filtering arbitrary datum which come from temperature sensor, deferential comparatoris used to calculating errorvalue, PIDcontrolblockis used as main control and serial communication block is used to establish communication with external hardware.

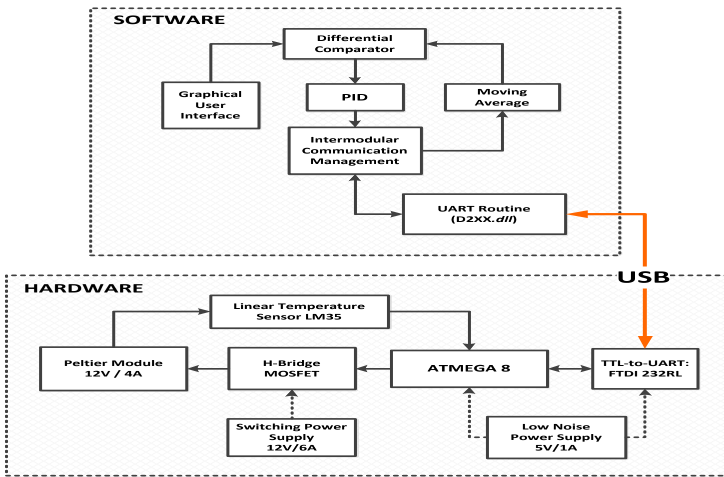

Figure 3 Block diagram of bovine'ssementemperature controller device

Hardware constructionconsists ofserialcommunication module to make communication with main software, an AT MEGA 8 microcontrollerto generatePWM signal as ordered from software calculation, H-bridgecircuit to buffer injected current into peltier module, lineartemperaturesensorLM35 to make real time temperature measurement,switching power supplyforH-bridgeandlow noise power supply for microcontroller and signal acquisition.

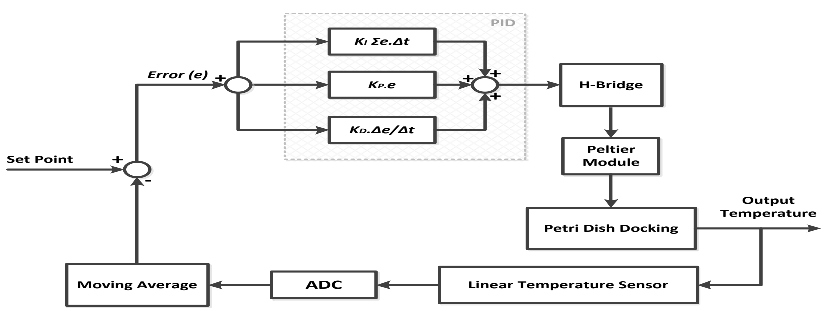

Figure4 PID control mechanism

When systemis turned on, software ordering hardware to getrealtimetemperaturestatus from peltier moduleandat the same time,PIDcontrol algorithmis executed by (17)to achieve given set point as fast as possible. A duty cycle calculation result from PID issent toAT MEGA 8 through USB serialcommunication.Duty cycle order came fromsoftware then translated by

AT MEGA 8 intoreal duty cycle value. PWM output signal from AT MEGA 8 which referred (21) injected to H-bridge MOSFET circuit. At the other side, a switching power supply which connected to peltier module through H-bridge is used to supplying peltier module's power demand. Using this scheme, peltier's passed current can be fully controlled using software andat the same time, a linear temperaturesensor(LM 35) measuringpeltier module'stemperature and send it to software as feedback. PIDcalibrationis performed using reference[8].

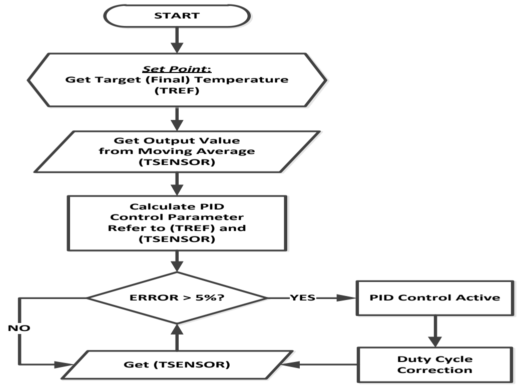

Figure5 Peltier module's temperature control method

4. Design results

Refer to diagramsin Figure3, 4and 5;bovine'ssementemperature controller consists of software andhardwarewhich can communicate each other through serialcommunication lines. Figure6 shows software appearance (GUI)which has beensuccessfully developed and Figure7 showsformed ice onpreparation holder(-seeredcircle) when peltiermodule is operated atmaximum coolingmode$(D = 100\%)$

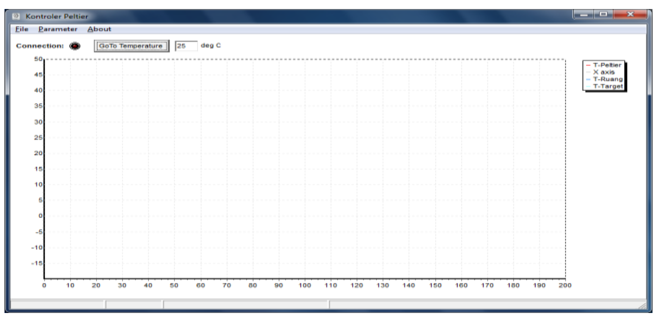

Figure6 Main softwareappeareance

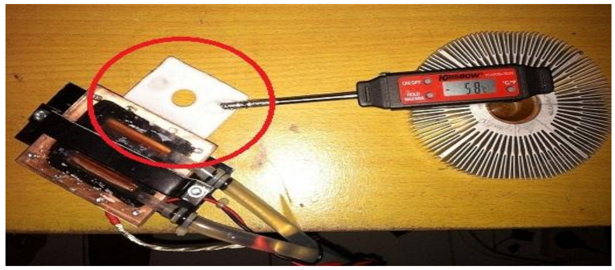

Figure7 Formed ice on bovine's semen preparation holder, *see red circle*

$$\left(T_{peltier} = -5{,}8^{o}C;\ D = 100\%;\ T_{ambient} = 25^{o}C\right)$$

5. Testing

Overall system was tested using two methods. First testing methodis using step testing signal toobtainpeltier module temperature responseversus input set pointprofile.Figure8 shows peltier module cooling responseand Figure9 shows peltier module heating response.

Figure8 Peltier module's cooling response ($40^{o}C$ to $10^{o}C$)

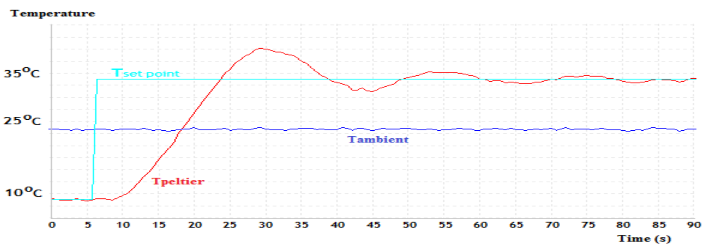

Figure9 Peltier module's heating response ($10^{o}C$ to $35^{o}C$)

From Figure 8 and Figure 9, it can be known if preparation holder temperaturehas maximumcooling rate $-0.9^{o}C/second$ and maximumheatingrate$1.7^{o}C/second$. It also seemsif steady-statetemperature condition is reached faster incoolingmodecompared to heatingmode. Overshoot is highly visible when systemis operated inheatingmode.

Secondtest method is performedby changing set point value continuouslyto obtain peltier module's steady-statetemperature response due to any setpointinput. This testaims to measure hardware output temperaturefidelity due to any desired input set point. Figure10 shows peltier module's linearity response profile ranging from $-30^{o}C$ to$50^{o}C$of set point command.Refer toFigure10, it canbe seenif hardwarehas lineartemperature responseprofile ranging from $-5^{o}C$ to $50^{o}C$ in standard testing temperature pressure$(25^{o}C/1\ atm)$. Set pointtesting over$50^{o}C$was not performed becauseuncontrollable overshoot potency which candamagepeltiermodule.

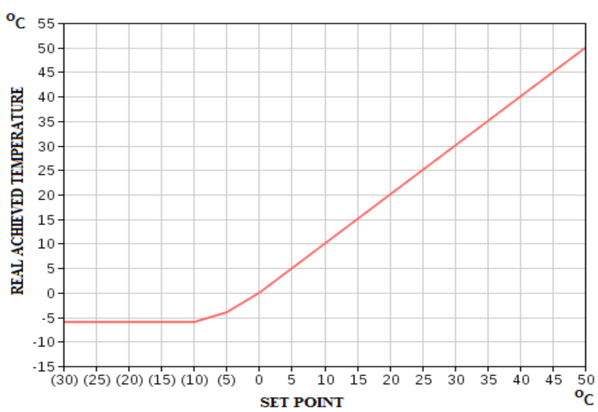

Figure 10Setpoint temperature fidelity responses

6. Conclusion

From testing results, it can be known if bovine's semen temperature controller has linear temperature response profile ranging from $-5^o C$to $50^o C$ in standard testing temperature pressure$(25^o C/1\ atm)$. System has maximum cooling rate $-0.9^o C/second$ and maximum heating rate$1.7^o C/second$. Heating control responses above ambient (room) temperature are not symmetrical with cooling control responses below ambient temperature;therefore this control system prototype still need further research to make adaptable control system for any temperature condition given.

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Appendix:

Figure A.1. Bovine's semen temperature control hardware

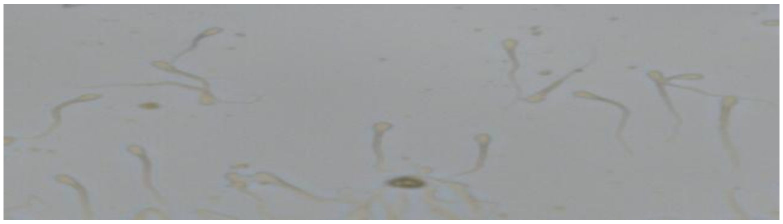

Figure A.2. Bovine's sperms at low temperature $(4^o C)$ hold for 15 minutes
(All bovine sperm's motility decreased to zero)