Development of a Heating Stage for an Optical Trapping Microscope

by

Lynn Wang

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Signature of Author..
Department of Mechanical Engineering
May 12, 2006

Certified by..
Matthew J. Lang
Assistant Professor of Mechanical Engineering and Biological Engineering
Thesis Supervisor

Accepted by..
John H. Lienhard V
Professor of Mechanical Engineering
Chairman, Undergraduate Thesis Committee

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ABSTRACT

The Lang Laboratory specializes in the study of biological systems through research using optical tweezers. Currently, experiments involving force and position manipulations of cellular molecules take place at room temperature. Experiments with these molecules have the potential to yield more information about biological systems were these experiments performed at the temperature at which the molecules naturally operate. Since the microscopes in the laboratory are geared with sensitive lasers, mirrors, and detectors that make up the optical traps, a custom designed microscope stage heater is necessary to execute research at body temperature (37°C). A custom temperature controller, equipped with controller unit and slide heating aluminum plates, is built to warm the slide sample to and maintain it at 37°C without interfering with the operation of the specified microscope.

Thesis Supervisor: Matthew J. Lang

Title: Assistant Professor of Mechanical Engineering and Biological Engineering

Introduction

The Lang Laboratory specializes in cellular and biomolecular research, using optical tweezers and single molecule fluorescence to uncover the intricate workings of biological systems (Lang Laboratory). The major instrument used to conduct the research is a microscope equipped with an optical trap, capable of applying piconewton forces to dielectric beads, sizing on the order of nanometers to micrometers. The beads can be attached to biological macromolecules via antibody-antigen attractions. The bead, and therefore the molecule, can then be controlled with the optical trap. This allows the performance of single-molecule experiments that yield specific information about the behavior of biological molecules.

Optical tweezers have a variety of experimental uses. They have been used as a force transducer to find the force versus displacement profile of unzipping a double stranded DNA helix. One strand of DNA is attached to the slide while the other strand is attached to a silica bead that is manipulated by an optical trap. The slide is displaced laterally. The force applied by the double helix as it unzips is measured by the bead position within the trap (Bockelmann et al. 1537). An optical trap can also be used to find the force of an actin myosin "working stroke." Veigel et al. have attached a bead to each end of the actin molecule, held by two optical traps, while a third bead anchored the myosin molecule to the slide. The force of the working stroke is measured by the displacement of the beads attached to the actin (Veigel et al. 1424). Optical tweezers can be used to research many such biological molecules.

The Lang Laboratory combines the optical trapping technology with that of single molecule fluorescence to better understand the mechanotransduction, cell mechanics, microrheology of complex solutions, receptor-ligand unbinding, and biological motors (Lang Laboratory). Currently, the experiments are performed at room temperature even though the normal operating temperature of most mammalian biological molecules are at 37°C. Therefore, a microscope stage heater needs to be created to heat the samples to 37°C and maintain that temperature throughout the duration of any given experiment.

The current microscope setup also includes other sensitive features such as a piezo stage and acusto-optic deflectors to obtain precise measurements of sample position. Due to the sensitivity and uniqueness of the microscope, a custom made temperature controller is required to simulate a cell-like environment for the samples without damaging or compromising the precision of the instrument.

There are several microscopes in the Lang Laboratory equipped with an optical trap and other sensitive apparatuses. One microscope is located in the basement of the Lang Laboratory. Due to the sensitivity of the microscope and the equipment with which it is geared, the instruments are isolated from ambient light and vibrations. The microscope also features single molecule fluorescence and a great extent of computer automation in addition to the optical trap. Another microscope can be found on the second floor of the laboratory featuring optical trapping and florescence imaging capabilities.

In addition to the research microscopes, there are also several smaller microscopes being designed for student use in laboratory classes. The student microscopes also have optical traps but are not as sensitive as the microscopes found in the laboratory.

Background

The Microscope

The microscope setups in the Lang Laboratory are geared with a highly sensitive optical trap that applies piconewton forces to spherical beads of a few microns in diameter. The sensitivity of the instrumentation requires a custom built temperature controller specific for the microscopes.

The optical trap works by focusing a laser beam through a high aperture objective lens on a dielectric particle in aqueous solution (Simmons et al. 1813). The scattering of photons transfers momentum to the particle. A gradient force, proportional to the intensity gradient of the beam and in the direction of the intensity gradient of the beam, counterbalances a scattering force, proportional to the intensity of the beam and in the direction of the beam (Ashkin et al. 288). Figure 1 diagrams a bead trapped by an incident laser A. As the light passes through the bead, the beam is scattered by the dielectric material, causing the transfer of momentum that produces the force F_A. When properly focused, the laser beam becomes a set of "optical tweezers," holding the bead in place.

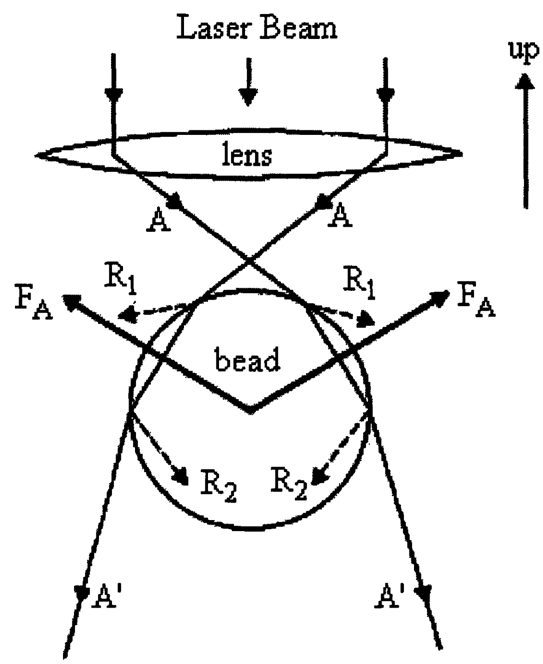


Figure 1: Incident beam, A, is focused by an optical lens then travels through the dielectric bead and is scattered by it, emerging from the bead as A′. The scattering of A creates the force F_A and surfaces reflections R_1 and R_2 (Ashkin et al. 288-289).

The optical trap can also be used as a force transducer to measure force fluctuations the trapped particle undergoes. When an external force is applied to the bead, the displacement of the bead is proportional to the force change. This displacement takes place in a time span on the order a few milliseconds (Simmons et al. 1813). With the help of a piezo stage and deflectors, the exact location of the trapped bead can be measured with precision on the magnitude of a few nanometers.

Although each microscope in the lab has different specifications, they share the same general components modeled from the optical trapping microscopes of the Block Laboratory at Stanford University (Lang Laboratories). The microscopes are inverted, with laser beam paths as shown in Figure 2. The inverted setup allows for a fixed stage and a moving objective so that coupling of the laser trap can be achieved more stably (Neuman and Block 2719). The sample slide sits on the microscope stage, with the objective below it and the condenser above it. The slide is separated from the objective below it and the slide cover slip from the condenser above by a layer of lens oil.

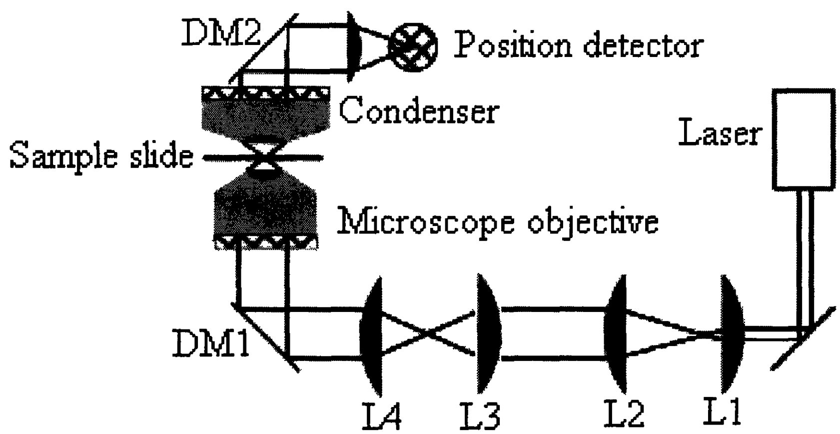


Figure 2: The beam originates from the laser source, travels through a series of lenses (L1-4), reflects off a dichroic mirror (DM1) which reflects incident light at the laser wavelength but transmits light at the illumination wavelength, and through the microscope objective to reach the sample. Once scattered by the sample, the beam travels through the condenser, is reflected off DM2, focused through another lens, and is finally absorbed by the detector (Neuman and Block 2789).

Since the functionality of the optical trap depends on the focus of the laser and the scattering caused by the bead, a temperature controller for the sample environment cannot interfere with the path of the laser. The temperature controller must allow the laser to pass through the objective, oil, glass slide, aqueous solution, bead, more solution, glass coverslip, more oil, and condenser without obstruction.

Commercial Temperature Controllers

Currently, there exist several different types of commercial temperature controllers designed for generic microscope stages. Unfortunately, none of these stage heaters can adequately serve the needs of the microscopes in the Lang Laboratory, although some of them have potentially useful ideas.

Some temperature controllers, such as that developed by Oko Labs, heat the sample environment by completely enclosing the sample in a clear, plastic well as shown in Figure 3. The well is then heated by circulating warmed water around the well (Oko labs). Fully enclosing the sample to regulate its temperature seems to be the most intuitive idea, but because of the precision of the optical trap laser, an enclosure cannot be used. The laser needs to travel from the objective to the condenser through the slide without other interference. Also, a stage heater that requires flowing water cannot be used for the Lang Laboratory microscopes because of the sensitivity of the optical trap and the piezo stage. Vibrations from the flow can disrupt the precision of the instruments. This design also has a layer of plastic above and below the sample, which would obstruct the path of the optical trapping laser.

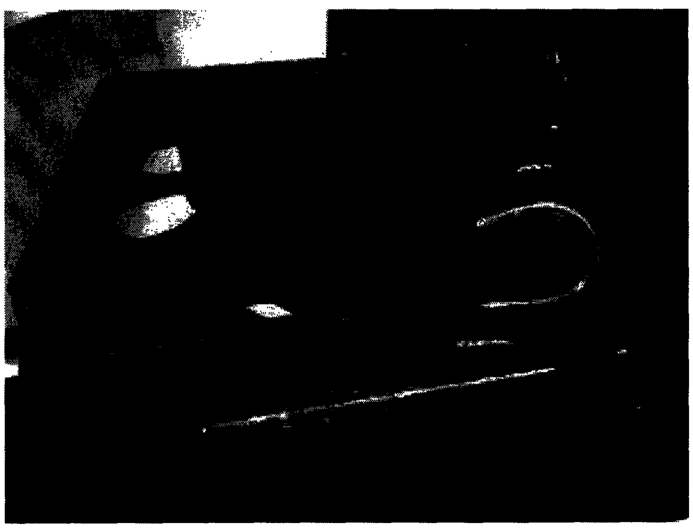


Figure 3: Temperature controller developed by Oko Labs. Samples are placed in the circular wells. The enclosure is then flooded with water to heat the samples.

Bioptechs offers a stage heater that uses an indium-tin oxide coating on a transparent slide to conduct heat through the slide itself (Figure 4). A gasket is sandwiched between the slide and the coverslip to allow room for the biological sample to be placed between the slide and coverslip. The system is regulated with a controller circuit box that regulates the current through the slide coating. An objective heater with its own controller circuit is a recommended accessory (Bioptechs). Although the concept of a self heating slide seems appropriate for an optical trapping microscope due to its ability to heat the sample without interfering with the trap beam, a non-disposable slide is not practical for the experiments performed in the Lang Laboratory. Often, molecules must be attached to an optical trapping bead on one end while attached to the slide on the other. Each sample must be prepared on clean, new slides. Current procedures for sample reparation also necessitate that the coverslip be adhered to the slide before the sample is run through the narrow space between slide and coverslip. The Bioptechs stage heater design does not allow for that method of sample preparation. Despite the unsuitability of the stage heater, the idea for an object heater is possibly useful.

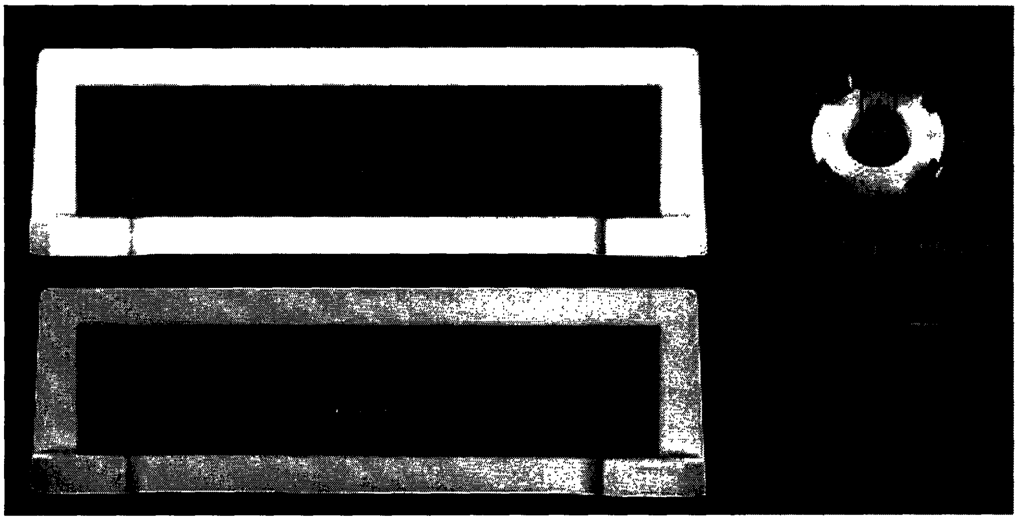


Figure 4: Bioptechs's design for a microscope stage heater (upper right), its controller circuit box (upper left), objective heater (lower right), and its controller circuit box (lower left).

Another model made by Instec, Inc., uses Peltier units to heat and cool a metal block that surrounds the slide (Figure 5). Such designs tend to bulky. Peltier heaters also require a separate cooling system that uses circulating water as the coolant (Instec). Once again, this creates disruptive vibrations to the system. Also, a cooling system is not necessary for the purposes of the research performed on the optical trapping microscopes.

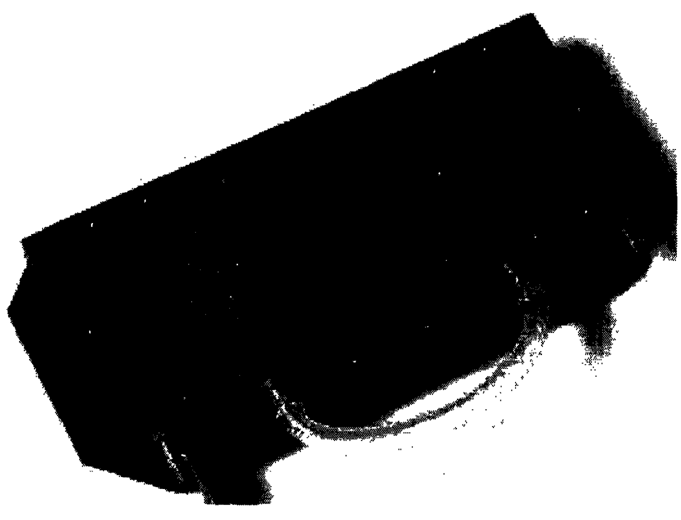


Figure 5: Instec's temperature controller that uses Peltier units to regulate sample temperature. The tubes used to the channel the coolant can be seen.

Design of Custom Stage Heater for Optical Trapping Microscope

Temperature Controller Feedback Circuit

The temperature of the stage heater is regulated by a controller box containing an Omega Microprocessor-Based Temperature/Process Controller connected to an Omega Solid State Relay with Vdc input and Vac output. The temperature controller is powered by 120Vac at 60Hz through a wall plug, which can be turned on and off through a rocker switch. The controller receives a thermocouple input of type K and outputs an on/off voltage signal of 0 to 5Vdc (Omega Engineering, Inc. "CN76000"). The output signal controls the solid state relay that switches a 120Vac current through the resistive heater, as shown in Figure 6.

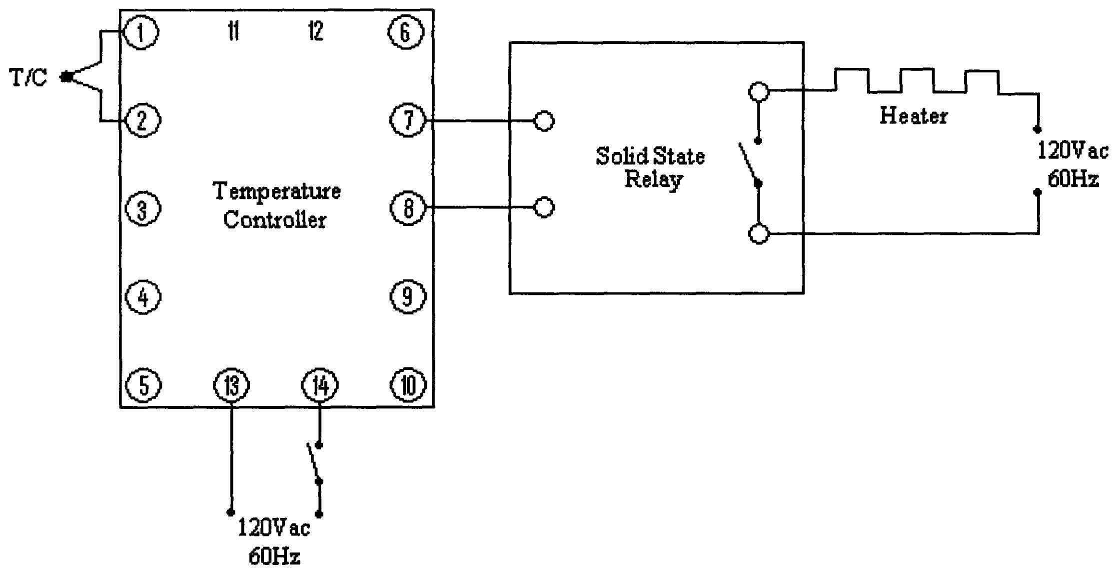


Figure 6: Circuitry within the temperature controller box. The numbered circles show all the available inputs and outputs to the controller as numbered on the back of the structure itself. The unused leads represent alternative wiring possibilities that are not suitable for this problem. Leads 1 and 2 of the temperature controller connect to the K-type thermocouple. Leads 7 and 8 connect to the solid state relay. Leads 13 and 14 connect to the power supply controlled by a rocker switch. The relay then controls the power to the heaters depending on the output from the temperature controller.

The temperature controller uses PID logic. This logic is most suitable for the purposes of regulating a stage heater because it will be able to gradually raise the temperature up to the set point and maintain it without overshooting. This type of logic is not vital for biological studies since the temperature deviations will not be large enough to affect the sample. The stage heater is also large enough to absorb sudden temperature deviations. However, the reliability in temperature is important when considering the thermal expansion of the stage heater material. Of the two metals tested for use as the stage heater—aluminum and copper—each will expand about 0.25μm per degree Celsius. Considering the precision of the optical tweezers and the piezo electric stage, the temperature deviations may cause significant movement of the stage.

The solid state relay is SPST and normally open. It is rated to turn on with an input of 3Vdc and off when the input drops below 1Vdc (Omega Engineering, Inc. "SSRL240"). When on, 120V of AC current flows through two heating elements (Figure 7) in series, warming the stage.

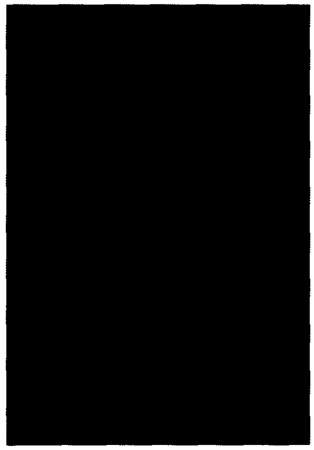


Figure 7: Top view of the heating element. The bottom (not shown) has a layer of adhesive.

The heating element consists of two 1"x1" fiberglass-reinforced silicone-rubber heat blankets by McMaster-Carr Supply Company that warm the stage through resistive heating. The heaters, connected to the controller system by banana plugs, are rated for a maximum output of 10 watts each (McMaster-Carr). Experimentally, the individual heat blankets vary in output. When connected in series to the 120 Vac current supplied by the wall plug, one heater warmed up to 54°C while the other warmed up to 46°C. Since both heaters are capable of supplying a temperature above the targeted 37°C, the performance variance between the two is not important. The wires leading from the heat blankets end in male banana leads for easy attachment to the controller.

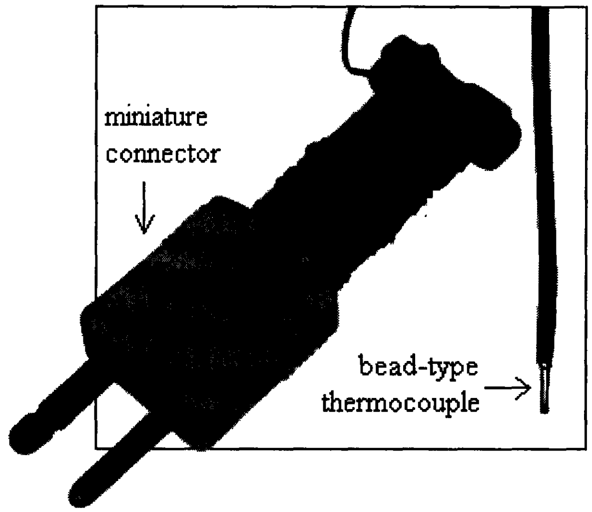


Figure 8: K-type thermocouple with miniature connector and bead-type sensing end (Omega Engineering, Inc. "Ready-Made").

One K- type, Teflon insulted thermocouple from Omega Engineering, Inc. supplies the input to the temperature controller (Figure 8). This type of thermocouple has been chosen because of its functioning temperature range (-200 to 1250°C), quick response, and small size. The bead-type sensing end of the thermocouple fits between the slide and coverslip, allowing the temperature measure measurement to be as close to the sample as possible. The other end of the thermocouple is attached to a male miniature connector. This can be easily plugged into and removed from the controller box.

The temperature control circuit system is enclosed by a plastic box into which openings were cut out with a handheld Dremel to mount the temperature controller and rocker switch. Interfaces for the thermocouple miniature connector, AC power, and heater are also created on the surface of the box.

(a)

(b) 

Figure 9: (a) Front of controller box showing Omega logic unit, K-type thermocouple female connector, female banana connectors for heating pads, and rocker switch. (b) Top of circuit box. The power cable to 120Vac wall supply can be seen.

Slide Heater

The stage heater is designed for the inverted microscopes in the Lang Laboratory, two of which are shown in Figure 10. Although the microscopes have different specifications, they are similar enough that the same stage heater design can be applicable to both. The main concern the design must accommodate is the optical trapping laser path. The stage heater must not interfere with the laser beam that runs from the objective to the condenser (Figure 11 offers a closer view of a condenser and an objective). The slide must also be able to move in the x and y directions so that samples can be searched for on the slide.

(a)

(b)

Figure 10: (a) Microscope on the second floor. (b) Student microscope. Both microscopes are inverted. The condenser is above the stage while the objective is below.

(a) (b)

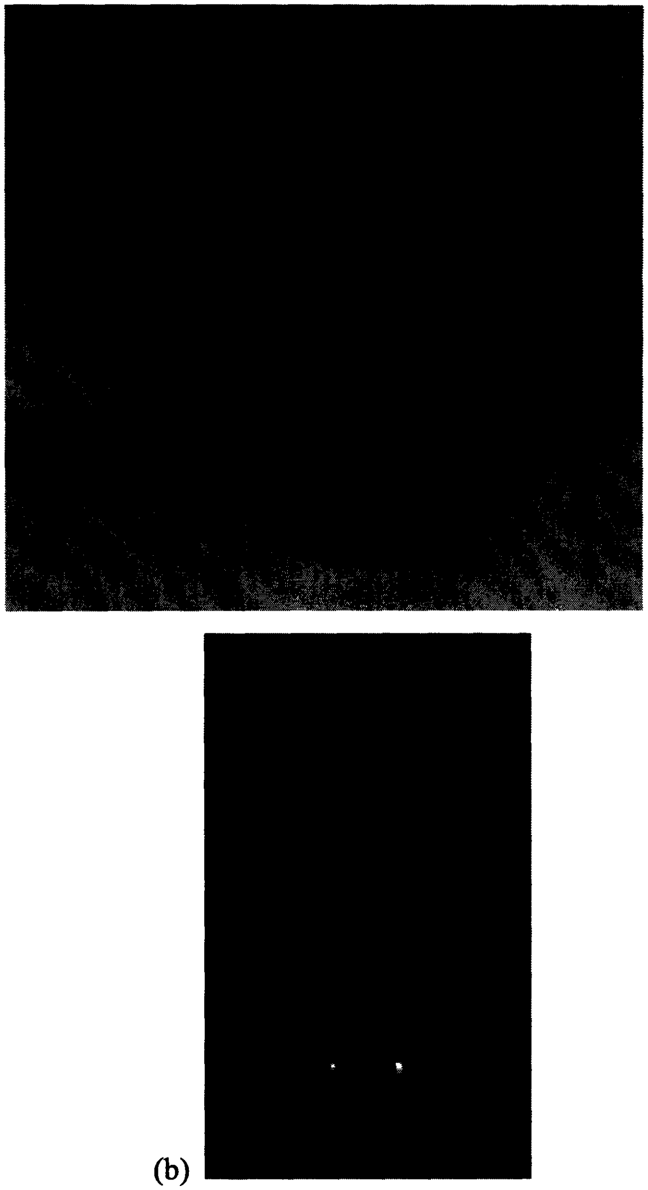


Figure 11: (a) Condenser. (b) Objective.

In light of these considerations, the final design involves two metal plates, between which the slide will be sandwiched. The dimensions of the plates are shown in Figure 12. Holes are cut into the plates so that the condenser and objective can contact the plate while creating a nearly closed space in which the slide resides. The plates are heated with the resistive heating blankets.

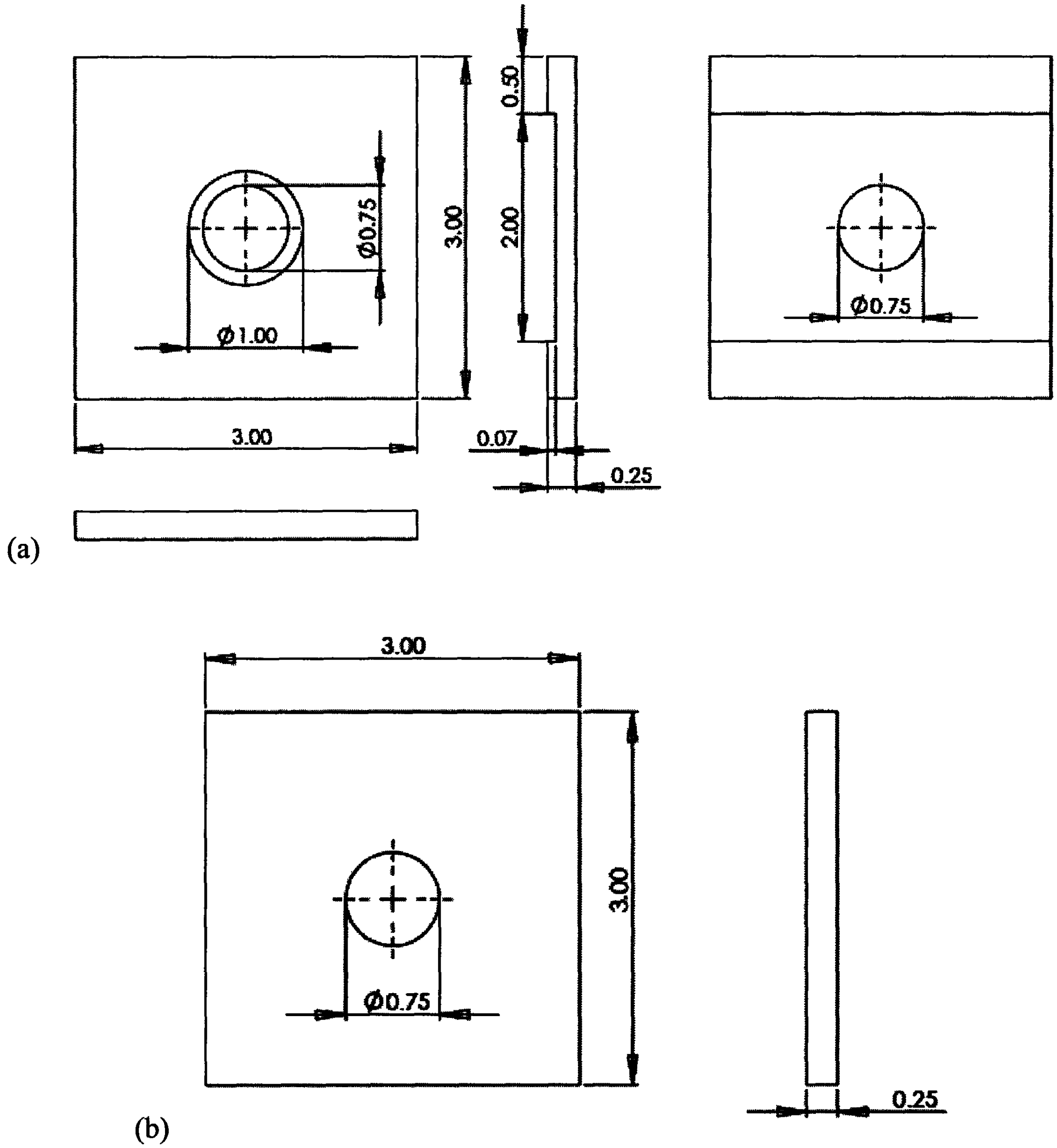


Figure 12: Stage heater design and dimensions (in inches). (a) Top plate. (b) Bottom plate.

Both plates are 0.25 inches thick and 3.00 inches square. The top plate has a 0.07 inch deep, 2.00 inch wide intrusion cut through the length of the plate (Figure 14) such that when the two plates are put together, the sample slide fits in between the two plates with enough room to move (Figure 13 b). The plates remain still as the slide can be moved in the x and y directions so that the experimenter can view all of the sample material that is on the slide. The resistive heaters are placed on the top plate, over where the slide resides beneath the metal. The heaters are placed against the sides of the condenser. This warms the condenser while reducing the amount of open space the slide is exposed to (Figure 13 a).

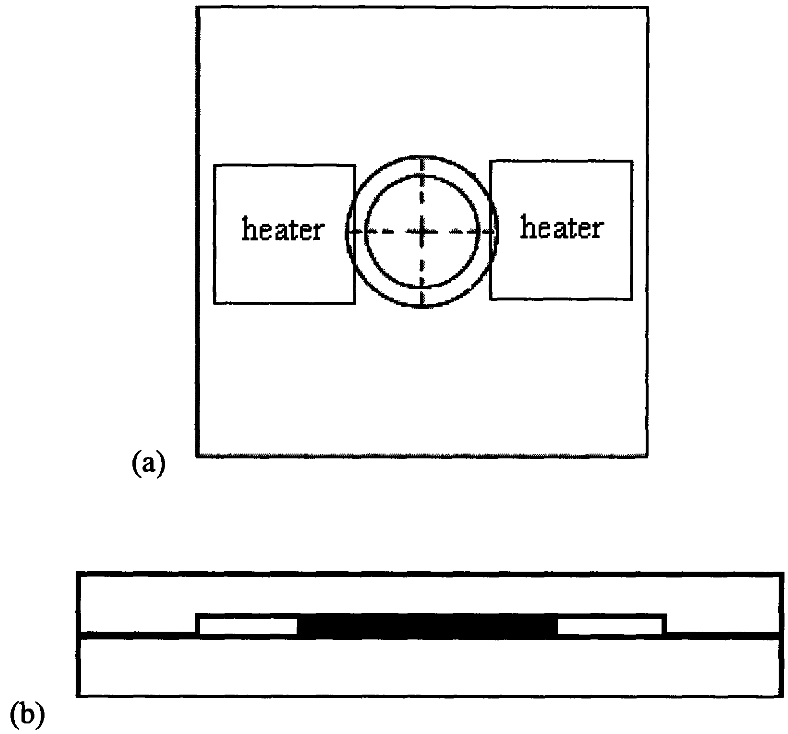
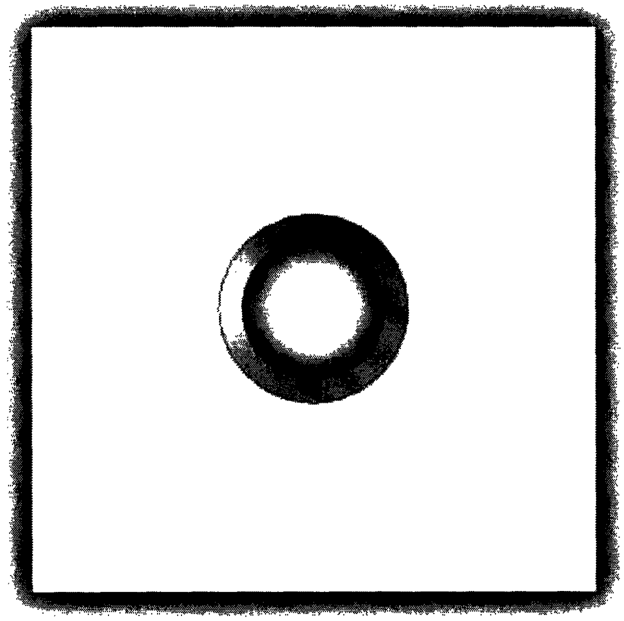
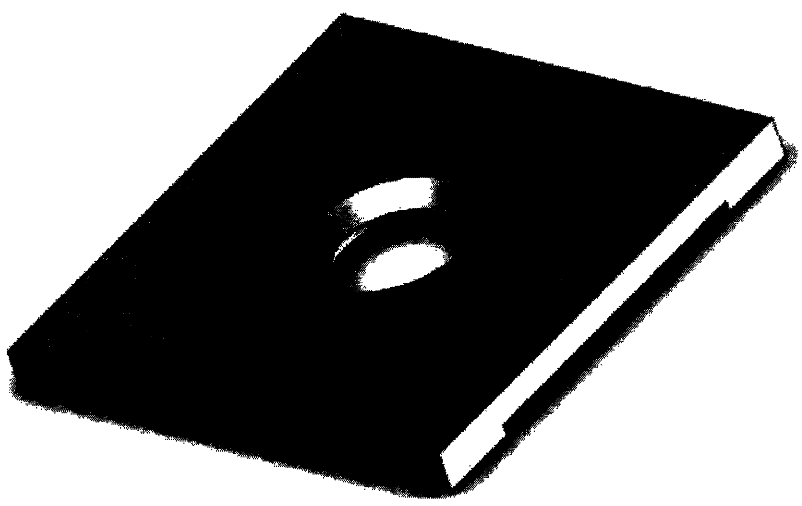


Figure 13: (a) Placement of heat blankets on the top plate. The heaters hang over the edge of the hole so as to make thermal contact with the condenser. (b) Side view of stage heater with the slide sandwiched (gray) in between. When the slide is in the middle of the plates, there is 0.50 inches on either side of it so that the experiment can move the slide to see every part of the sample.

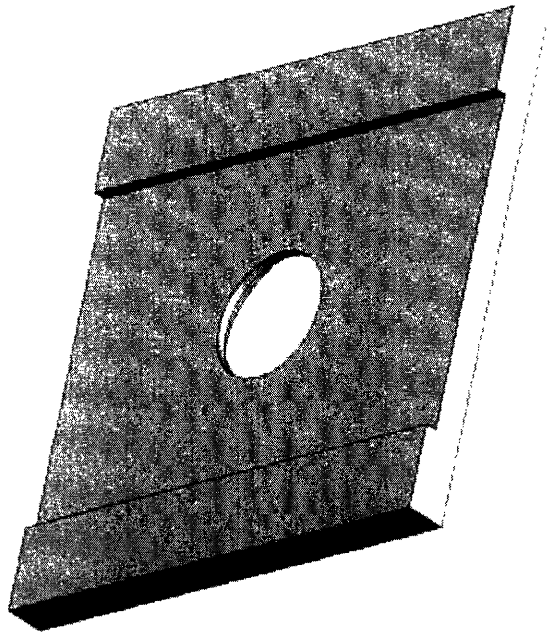
The chamfered hole at the center of the top plate allows the condenser to contact the slide. Although there is no seal between the plate and the condenser, the chamfer minimizes the exposure of the slide to ambient air that might affect the temperature of the sample.



(a)



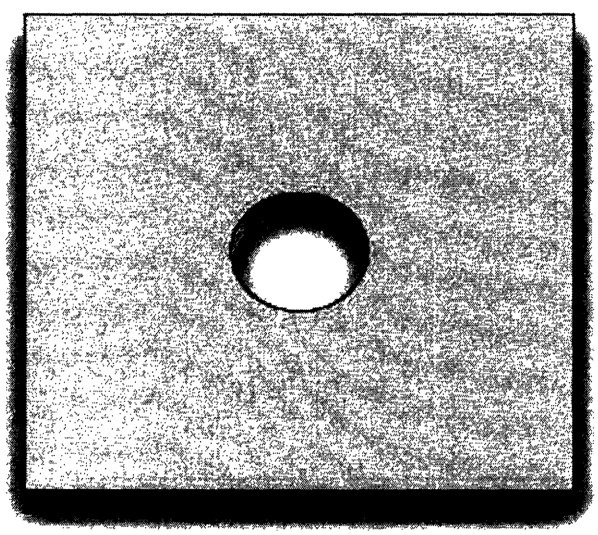
(b)



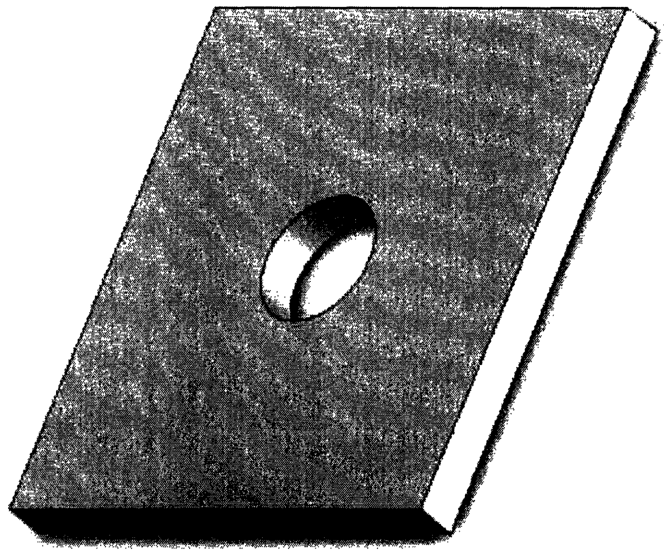
(c)

Figure 14: Solidworks models of the top plate. (a) Top view showing the chamfered hole. (b) Angled side view showing both the top and the side. (c) Bottom view to show the extruded space for the slide and the back of the center hole.

The bottom plate has a hole cut in the center of it to allow the objective to meet the slide. There are no heaters on the bottom slide because it is in thermal contact with the top slide. Relative to the glass slide, the metal transfers heat quickly so that there is no need for extra heaters.



(a)



(b)

Figure 15: Solidworks models of the bottom slide. (a) Top view. (b) Angled side view.

Once the design of the stage heater was completed, aluminum, copper, and brass were considered as possible materials with which to produce the stage heater because they are three easily available and inexpensive metals. The material needs to have a high thermal conductivity, high specific heat capacity, and a low coefficient of thermal expansion (CTE) over the range of about 15-40°C. A high thermal conductivity ensures that the metal can adequately transfer heat from the top plate to the bottom plate and from the plates to the glass slide. A high specific heat capacity reduces the possibilities of temperature fluctuations due to ambient air currents, accidental touching, or any other form of thermal contact with an object of a different temperature. A low CTE over the operating range prevents small fluctuations in temperature from interfering with the optical trap or the piezo stage during the course of an experiment. Because the instrumentation of the microscope is so sensitive, a few micros of linear expansion due to temperature changes can effect the focusing of the optical trap laser or location of the piezo stage.

Table 1 shows the thermal properties of aluminum, copper, and brass. While copper has the highest thermal conductivity and the lowest CTE, its specific heat capacity is very low compared to that of aluminum. Brass has poor thermal conductivity and low specific heat capacity and is, therefore, quickly eliminated as a possible stage heater material.

Table 1: Thermal properties of aluminum UNS A91100 (1100-O alloy), cold-worked copper, and brass UNS C36000.

	Al	Cu	Brass
Thermal Conductivity W/m-K	222	385	115
Coeff. Of Thermal Expansion μm/m-°C	23.6	18.5	20.5
Specific Heat Capacity J/g-°C	0.904	0.385	0.380

Tests with aluminum and copper versions of the bottom plate showed that the difference in performance between the two metals was negligible. The design shown in Figure 12c was machined in both aluminum and copper. The two heating blankets were applied to one metal then the other as shown in Figure 13a and heated. The higher specific heat capacity of the aluminum causes it to heat up slightly more slowly. Once at 37°C, the plates were placed in an environment of 22°C then moved to one of 10°C (surrounded by ice). Neither metal was noticeably affected by the ambient temperature change. This was probably due to the fact that the plates were massive enough that changes in temperature of the air were not enough to affect either metal.

The same experiment was repeated with a slide in thermal contact with the plate and the temperature being measured at the center of the slide. The ambient temperature greatly affected the temperature of the slide with both metals because of the poor thermal conductivity of the glass slide. Tests showed that even after 15 minutes of heating the slide with only one plate, the center of the slide measured 25.4±1.0°C (room temperature being 22.0±3.0°C) when the plate is 46.5±1.3°C. The difference in performance between the two metals was negligible considering the degree of error.

Since there was so little difference in the performance between the two metals, aluminum was chosen for its machinability. Aluminum would allow for the stage heater to be more easily manufactured and for the design to be more easily changed if a flaw were to be found. Since there were no major factors causing one metal to outperform the other, aluminum was chosen to ease production.

Once the material for the stage heater was chosen, it became evident that the slide must be further isolated from the ambient air. The current design was then devised. This design sandwiches the slide between two plates, giving the slide more thermal contact with the heat source. The exposed part of the slide (the space around the objective and the condenser) is minimized by fitting the holes to the shape of the condenser and objective (Figure 16). The contact between the condenser and the heating elements warms the area that is directly over the sample. The aluminum plates are shown by Figure 17.

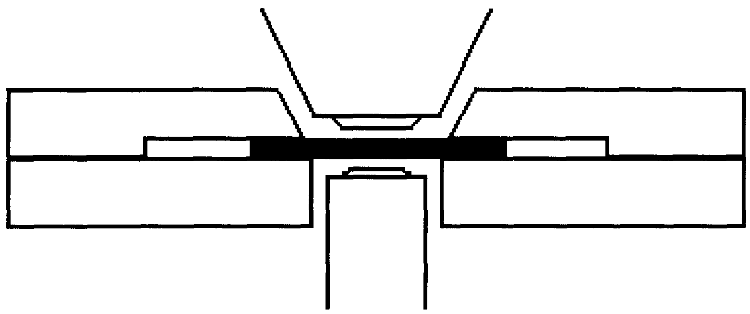
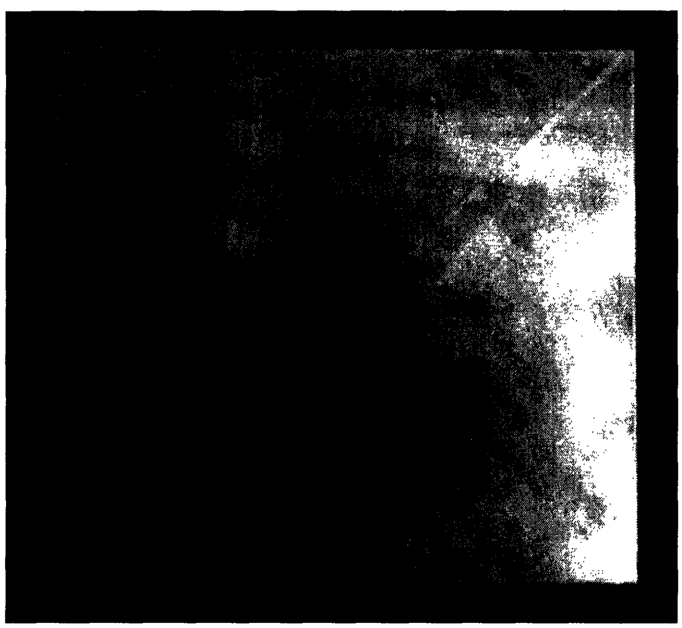


Figure 16: Cross-sectional view of the stage heater, condenser, objective, and slide (gray). The condenser is above the slide. The objective is below it. The blocks gripping the slide are the top and bottom plates.



(a)

(b)

(c)

Figure 17: Stage heater plates. (a) Top plate. (b) Bottom plate. (c) Top view of the plates stacked together.

The slide should be placed in between the aluminum plates with the thermocouple as close to the sample location as possible. The suggested way to do this is shown in Figure 18. Samples are normally prepared by first taping the coverslip onto the slide, leaving a narrow channel down the middle of the slide. The aqueous sample is then flowed through the channel. The thermocouple should be placed between the slide and the coverslip. Due to the thickness of the thermocouple, a few (about 4) layers of doublesided tape should be used, with a small sliver cut out of the tape to make room for the thermocouple.

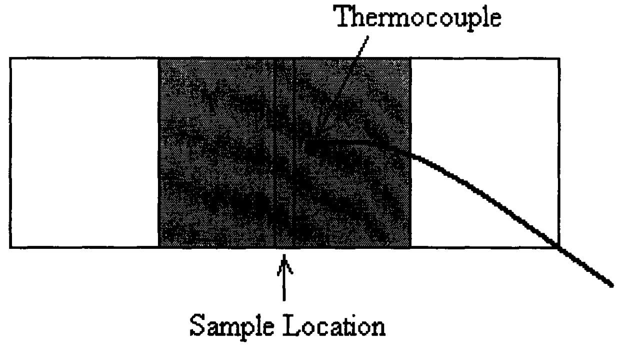


Figure 18: The microscope slide is shown with the thermocouple placed as close to the sample location as possible. The channel down the middle of the slide holds the sample. The thermocouple is taped beneath the coverslip (gray), near the sample without touching the sample.

The major drawback of this design is the preparation time. The setup requires about 20 to 30 minutes to warm. This is due to the large mass of the objective and condenser. The aluminum plates achieve over 40°C within 3 minutes of heating, but the objective and the condenser are not as thermally conductive, and they do not have as much thermal contact with the heating elements. This was intentionally done because direct contact between the heating elements and the objective or condenser has the potential to damage the equipment.

A good way to warm the setup is to place a dummy slide in between the plates first. The slide should have the thermocouple attached to it so that the experimenter can monitor the temperature of the equipment. The miniature connector clips are engineered onto the controller box for this purpose. Multiple slides can be prepared with the thermocouple attached at the correct place, and the thermocouples can be attached and detached from the controller unit.

Conclusion

The design of this stage heater allows for the performance of experiments using the optical trap microscope at body temperature. It heats the sample slide without interfering with the laser of the optical trap. The autonomous feedback circuit moderates the temperature without the active attention of the experimenter.

The stage heater plates are designed for experiments at a steady temperature. The system is not designed for experiments involving temperature changes. Not only is the system not capable of rapid temperature changes, the effects of thermal expansion of the aluminum plates over a large temperature change have not been thoroughly tested. Since expansion occurs linearly with increasing temperature of the metal, and ambient temperature changes do not cause a noticeable affect on the temperature of the plates, thermal expansion is not a concern when experiments are performed at steady temperatures. This design can serve as a foundation for further work to develop a microscope temperature controller capable of rapid temperature changes to study the effects of temperature changes on biological molecule function.

The heater blankets have the capability to warm a slide from room temperature up to about 40°C in its present circuit configuration. The system can be easily modified for higher temperatures by using more heating blankets and by putting more current through them. A microscope stage heater at higher than body temperatures can be used to study the function of biological systems that operate at volcanic temperatures.

Since the heating blankets do not have cooling capabilities, the temperature controller cannot lower the temperature of the microscope slides. However, the design of the aluminum plates can possibly be used to cool slides in the same manner that they help to heat them. The major obstacle in this endeavor is to find a method of cooling that does not require the flow of coolant. Vibrations caused by moving fluid would interfere with the instrumentation of the microscope.

The design of this microscope stage heater allows for the study of biological systems at their normal operating temperature. The design also has the potential for further innovations in the future.

WORKS CITED

"Aluminum 1100-O." Matweb Material Property Database. Automation Creations, Inc. 9 April 2006. http://www.matweb.com/search/SpecificMaterial.asp?bassnum=MA1100O.

Ashkin, A., Dziedzic, J. M., Bjorkholm, J. E., and Chu, Steven. "Observation of a Single-beam Gradient Force Optical Trap for Dielectric Particles." Optics Letters Vol.11, No. 5: 288-290, May 1986.

Bioptechs. "The Focht Chamber System (FCS2)." Online. http://www.bioptechs.com/Products/FCS2/fcs2.html. 3 May 2006.

Bockelmann, U., Thomen, P., Essevaz-Roulet, B., Viasnoff, V., and Heslot, F. "Unzipping DNA with Optical Tweezers: High Sequence Sensitivity and Force Flips." Biophysical Journal Vol. 82: 1537-1553, March 2002.

"Copper, Cu: Cold-Worked." Matweb Material Property Database. Automation Creations, Inc. 9 April 2006. http://www.matweb.com/search/SpecificMaterial.asp?bassnum=AMECu01.

"Free-Cutting Brass, UNS C36000, M30 Temper Shapes." Matweb Material Property Database. Automation Creations, Inc. 9 April 2006. http://www.matweb.com/search/SpecificMaterial.asp?bassnum=MCUACD05.

Instec, Inc. "HCS60: Hot and Cold Stage for Inverted Microscopes." Online. http://www.instec.com/products/stages/hcs60.html. 3 May 2006.

Lang Laboratory. "Lang Laboratory: Research." Online. http://web.mit.edu/~langlab/Research.html. 15 March, 2006.

McMaster-Carr Supply Company. "Heat Blankets: Standard Fiberglass-Reinforced Silicone-Rubber Heat Blankets." McMaster-Carr Product Catalog: 474. 2006.

Neuman, K. C. and Block, S. M. "Optical Trapping." Review of Scientific Instruments Vol. 75, No. 9: 2787-2809.

Oko Labs. "CO2 Microscope Stage Incubator: The Ultimate Solution for Time-Lapse Experiments." Online. http://www.oko-lab.com/39.page. 15 March, 2006.

Omega Engineering, Inc. "CN76000 Microprocessor-Based Temperature/Process Controller." Product Manual No. M1303, December 2003.

Omega Engineering, Inc. "Ready-Made Insulate Thermocouples." Omega Product Index: A23. 2003.

Omega Engineering, Inc. "SSRL240 Series and SSRL660 Series Solid State Relays." Online. Product Manual No. M3813, May 2002.

Simmons, R. M., Finer, J. T., Chu, S., and Spudich, J. A. "Quantitative Measurements of Force and Displacement Using an Optical Trap." Biophysical Journal Vol. 70: 1813-1822, April 1996.

Veigel, C., Bartoo, M. L., White, D. C. S., Sparrow, J. C., and Molloy, J. E. "The Stiffness of Rabbit Skeletal Actomyosin Cross-Bridges Determined with an Optical Tweezers Transducer." Biophysical Journal Vol. 75: 1424-1438, September 1998.