DEVELOPMENT OF STEADY-STATE MIRRORS FOR THE KSTAR ECH LAUNCHERS

R. Ellis[1], Y. S. Bae[2], J. Hosea[1], M. Joung[2], D. Miller[1], W. Namkung[3], H. Park[3]
[1]Princeton Plasma Physics Laboratory, Princeton, NJ, USA
[2]National Fusion Research Institute, Daejeon, Korea
[3]POSTECH, Pohang, Korea
Corresponding author e-mail: rellis@pppl.gov

Abstract— Steerable Electron Cyclotron Heating (ECH) launchers typically use a fixed, focusing mirror and a flat steerable mirror to direct a high power beam. The launchers presently in service on KSTAR are intended for use in pulsed operation and are passively cooled.

KSTAR, and its ECH system, will eventually operate at pulse lengths where a steady-state balance between input power and heat removal must be achieved. Initial design studies for ECH launcher mirrors have been performed, and a prototype has been fabricated and tested.

This paper describes the design studies for steady-state ECH launcher mirrors considered for the KSTAR system. Results of analyses and prototype tests are described.

Keywords—electron, cyclotron, heating

I. INTRODUCTION

Electron Cyclotron Heating (ECH) and Electron Cyclotron Current Drive (ECCD) are essential to the operation of advanced tokamaks[1,2,3]. Heat and current drive can be deposited at precise locations in the plasma, and ECCD can be used for suppression of Neoclassical Tearing Modes[4] (NTM), for current profile[5] and plasma rotation control, and other applications.

An ECH/ECCD system typically consists of a gyrotron, which supplies a millimeter-wave beam at about 1MW; a low-loss waveguide, which transmits the power from the gyrotron to the tokamak; and finally the launcher, located on the tokamak, which directs the beam to its desired location in the plasma. A combination of a fixed, focusing mirror and a flat, steerable mirror are used for beam shaping and steering. [Figure 1]

ECH systems have evolved in recent years, with higher power, pulse length and frequency gyrotrons becoming available, and increased launcher capability. In 2001, PPPL delivered the P2001 ECH launcher to the DIII-D project[6]. This launcher, first in a series of four, provided steering in the toroidal direction from co- to counter-injection, and in the vertical direction from below the midplane to the top of the plasma, for two 1MW, 10 second, 6cm diameter beams. Steering was remotely controlled using motors, and encoders for position feedback. The fourth launcher was delivered in 2011. Its mirrors enabled the use of a 1.5MW, 10sec gyrotron, and it had fast poloidal steering to enable tracking and suppression of NTMs. The other three launchers were all upgraded to the same specification.

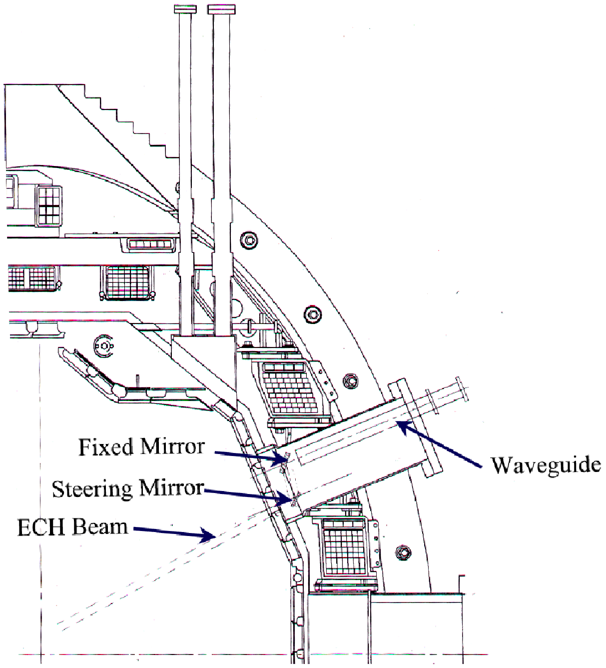

Fig. 1. Schematic view of an ECH launcher on DIII-D

II. OVERVIEW OF THE KSTAR ECH LAUNCHERS

In 2006, PPPL delivered the first KSTAR ECH launcher[7] [figure 2], with mirrors and steering gear identical to the DIII-D P200x launchers, and adapted to the KSTAR midplane port geometry. A second launcher of the same design, to be used with the new 170GHz system[8], was delivered in 2011. This launcher was upgraded in 2013 with the latest DIII-D style mirrors[9]. These mirrors are passively cooled, meaning that they cool during long intervals between pulses by radiating heat. The large temperature excursions inherent in this type of design result in significant thermal fatigue stresses, and these mirrors are thus “finite life.” There are designed for one run year of 4000 shots at 1.5MW, 10s. This is roughly equivalent to 1MW, 15s, and the pulse length could be extended to 20 seconds at the cost of some fatigue life.

KSTAR will soon operate at pulse lengths that will require mirrors designed for steady-state operation. A first step toward this goal is to design, build and install an actively cooled, steady-state fixed mirror on the 170 GHz launcher. This will provide operational experience and a design basis for an actively cooled steerable mirror. A description of our work on the actively cooled fixed mirror follows.

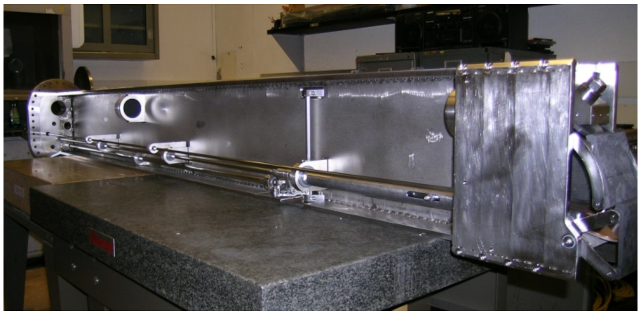

Fig. 2. KSTAR ECH Launcher

III. DESIGN PARAMETERS OF THE STEADY-STATE FIXED MIRROR

The power flux of the beam emerging from the waveguide is expressed as

$$Q''(r) = Q''_{\max} J_0^{\,2}(r),$$

where r is the distance from the beam axis and J_0 is the Bessel function of the first kind, order zero. Typically r is normalized to z_1, the first zero of J_0, and we have $r' = rz_1/a$, where a is the half width of the mirror, and this definition implies that the beam is expanded to the width of the mirror. The normal to the mirror is tilted 50 degrees from the axis of the beam, and the circular beam is projected onto the mirror surface as an ellipse with long axis $b = a/\cos(50°)$. Absorbed power is calculated from the formula[10]

$$A = 1 - R = 4\sqrt{\pi f \rho \varepsilon_0}.$$

For copper, the resistivity $\rho = 1.72*10^{-8}\,\Omega - m$. Free space permittivity is $8.85*10^{-12}\,F/m$. The absorbed fraction, A, is therefore between .0008 and .0011. Operational experience, where the beam reflection can be degraded by material deposited on the mirror surface, suggests the use of 0.2 per cent in thermal analyses. The heat flux at the mirror surface is thus

$$q'' = q''_{\max} \left|J_0(xz_1/a)\right| \left|J_0(yz_1/b)\right|$$

The launcher design prevents heat radiated by the plasma from reaching the fixed mirror, so the heat load is due entirely to the microwave beam. For our power and beam parameters, peak heat flux is 84W/cm^2.

The mirror is water cooled with forced convection. It is assumed that a film coefficient of 1W/cm^{2}K can be achieved, and that the coolant flow path will have a diameter of 8mm [.31in].

IV. DESIGN OVERVIEW

A successful water-cooled, steady-state mirror must have adequate convection and conduction between the coolant and the reflecting surface, and adequate coolant flow to provide a steady-state power balance. Conduction between the fluid boundary and the reflecting surface is proportional to the thermal conductivity and inversely proportional to the distance between the two. Electromagnetic forces, due to eddy currents during a disruption, are typically proportional to the mirror thickness and conductivity. A thin layer of material between the fluid and reflecting surface maximizes heat transfer and minimizes electromagnetic forces, but is more susceptible to catastrophic failure than a thick boundary. We chose to use a thicker, high conductivity mirror made from copper alloy, with adequate coolant surface area and a modest film coefficient. Some fundamental calculations based on this design philosophy, presented below, lead quickly to an initial design.

The mirror is widened to 7.62cm [3.00in], which is compatible with the existing structure. The mirror tilt dictates a length of 11.43cm [4.50in].

A film coefficient of 1W/cm^{2}K is assumed, based on experience, and will be verified later. At the center of the mirror, we have the steady-state heat flux balance

$$85W/cm^2 = \left(1W/cm^2K\right)\left(\Delta T\right),$$

and therefore $\Delta T = 85K$. The minimum copper thickness between the cooling water and reflecting surface is 0.24cm [.094in]. The steady-state heat flux balance across the copper is

$$85W/cm^2 = k\left(\frac{\Delta T}{.24cm}\right).$$

Using $k = 3.91W/cmK$, the temperature drop is 5K. Assuming a 20C bulk temperature for the coolant, the front surface temperature will be

$$T = 20 + 85 + 5 = 110C.$$

The mirror will use six coolant channels, .79cm [.313in] diameter, connected in series. Using an assumed flow velocity of 305cm/s [10ft/s], the Nusselt number can be calculated using the well-known formula[11]

$$Nu_d = \frac{hd}{k} = .023\,\mathrm{Re}^{.8}\,\mathrm{Pr}^{.4},$$

Where Pr is the Prandtl number, Re is the Reynolds number, d is the diameter, k is the thermal conductivity of water, and h is the film coefficient. The Reynolds number is defined as

$$\mathrm{Re} = \frac{Ud}{\nu},$$

where U is the fluid velocity and ν is the kinematic viscosity. For water[12] at 20C, $k = .00604W/cmK$, $\mathrm{Pr} = 6.78$, $\nu = 9830cm^2/s$, and $\mathrm{Re} = 2.45*10^4$. Substituting, we obtain

$$Nu_d = 161, \text{ and } h = 1.23W/cmK.$$

The required pressure for our flow velocity can be calculated as the product of the friction factor, the length-to-diameter ratio of the coolant lines, and the dynamic pressure of water at 305cm/s. Based on the launcher geometry, we assume 500cm of coolant tubing. Thus

$$\frac{l}{d} = \frac{500}{.79} = 633.$$

The dynamic pressure of water is

$$P_d = \frac{1}{2}\rho V^2 = 0.5\left(1g/cm^3\right)\left(305cm/s\right)^2$$
$$= 46512dyne/cm^2 = .67psi$$

Using the well-known Moody diagram[13], we estimate the friction factor $f = .025$ and $f\frac{l}{d} = 15.8$. The required pressure drop is therefore

$$P = 15.8\left(46512dyne/cm^2\right)$$
$$= 7.35*10^5 dyne/cm^2 = 10.6psi$$

Finally, the bulk temperature rise of the water is estimated. The mass flow is

$$\dot{m} = 1g/cm^3\left(\frac{\pi(.79cm)^2}{4}\right)\left(305cm/s\right) = 150g/s.$$

The absorbed power is

$$Q = .002\left(8*10^5W\right) = 1600W,$$

and the bulk temperature rise is

$$\Delta T = \frac{1600W}{\left(150g/s\right)\left(4.2J/gK\right)} = 2.5K.$$

V. INITIAL MIRROR PROTOTYPE

An initial mirror prototype [Figure 3] was constructed from a block of copper, with semicircular grooves for the cooling tubes milled in. Tubes were brazed in, and the series connections were made with standard soldered tube fittings. A rectangular ceramic heater, capable of 1453W, was applied to the center of the front surface. Finite element thermal analyses of the mirror were performed in ANSYS, using the heat deposition from an EC beam and from the heater [Figures 4 and 5]. The model of a quadrant of the mirror [figure 6] took advantage of symmetry, neglecting the small rise in coolant bulk temperature, and used SOLID278 and SURF152 elements. A film coefficient of 1.0 was used. The temperature distribution resulting from the heater is representative of that from the beam. These analyses also showed that the temperature of the front surface was acceptable.

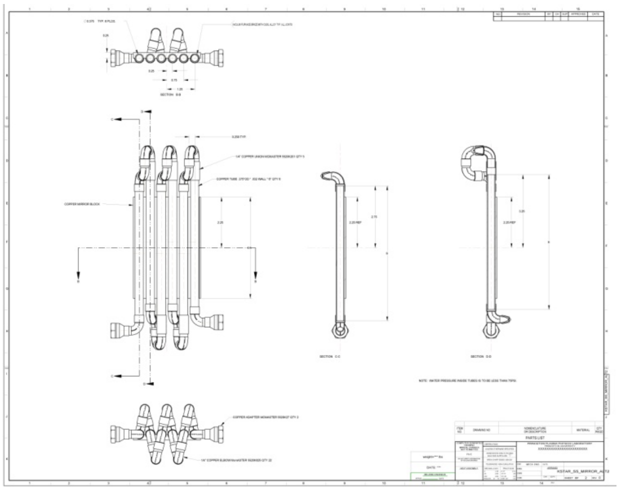

Fig. 3. First Mirror Prototype

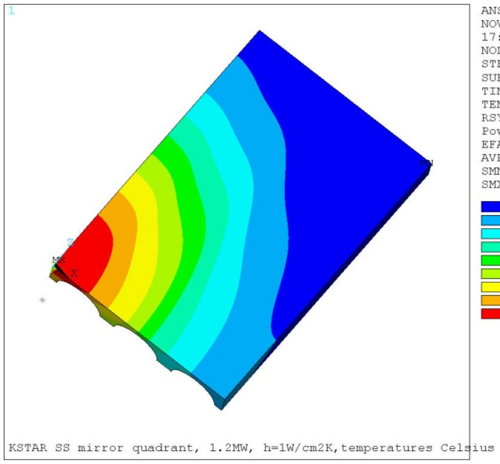

Fig. 4. Thermal Analysis – Gyrotron Heating

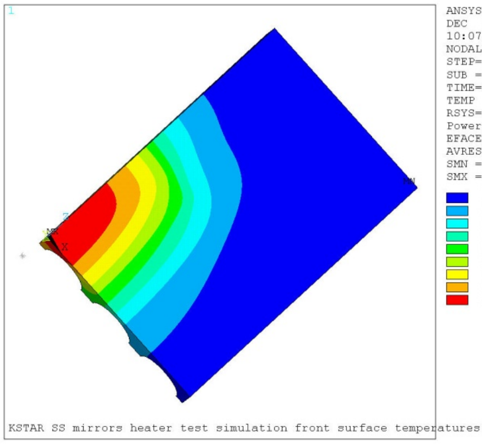

Fig. 5. Thermal Analysis – Ceramic Heater

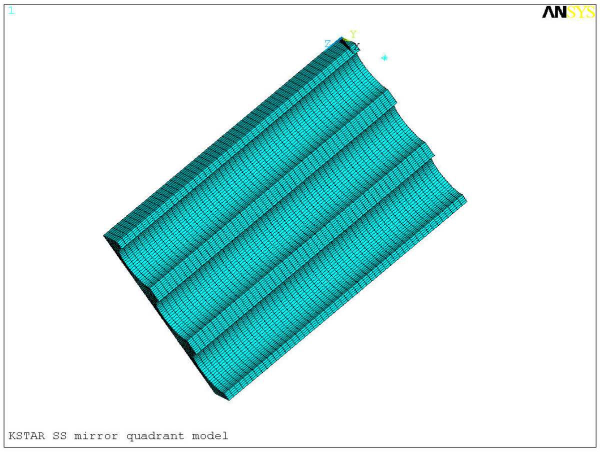

Fig. 6. Thermal Model of Mirror Quadrant

Initial testing with the prototype showed that the temperature at the center of the heater was 74C.

VI. DESIGN OF THE SECOND MIRROR PROTOTYPE

A second mirror prototype, to be constructed from C18150, has been designed. [Figure 7] The ends of the mirror, where the series connections of the cooling tubes are made, are now more representative of what will be installed on the launcher. Additional analyses have been performed: a thermal stress analysis, as well as an analysis of eddy currents, Lorentz forces, and the resulting stresses.

The ANSYS thermal model, as before, used SOLID278 and SURF152 elements and represented one quadrant of the mirror. For thermal stress analysis, the elements were switched to SOLID185. Free expansion boundary conditions were applied. The maximum von Mises thermal stress [Figure 8] was 7.5N/cm^2 [10.9ksi]. Applying this stress to a Soderberg diagram, with the mean and alternating stress both 3.75N/cm^2, [5.45ksi] we see that the stress is below the million-cycle line for C18150. [Figure 9]

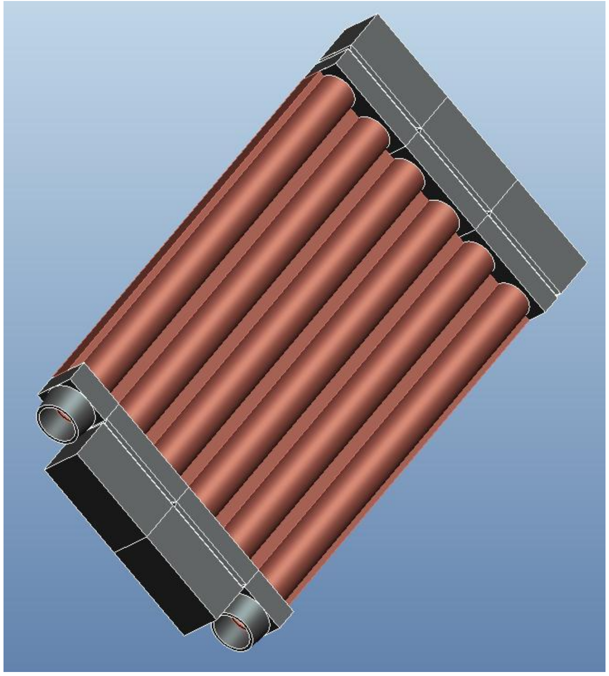

Fig. 7. Second Mirror Prototype, Back View

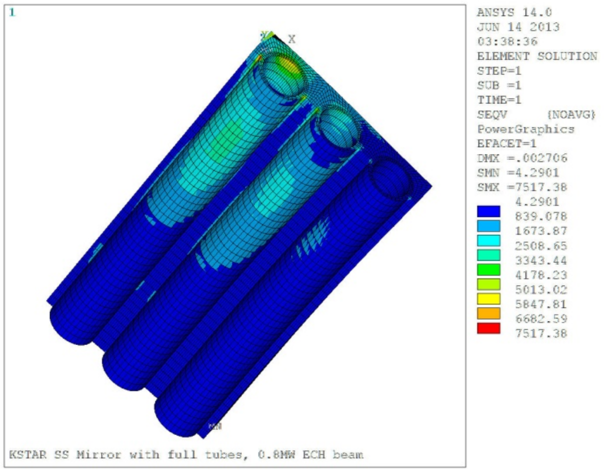

Fig. 8. Von Mises Thermal Stress

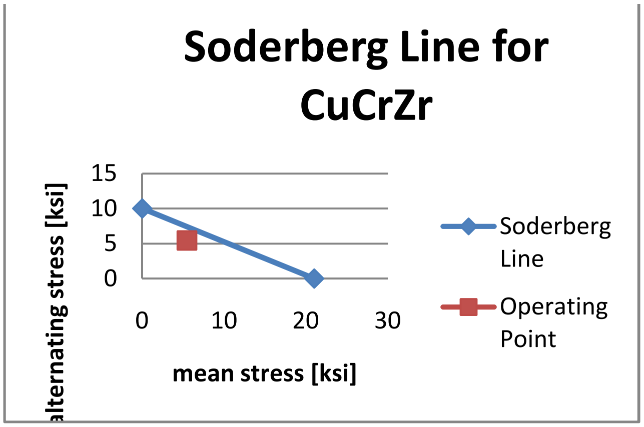

Fig. 9. Soderberg Line for C18150

Electromagnetic analyses used SOLID97 elements, and the full mirror geometry was modeled.

Currents flowed primarily in the front surface of the copper portion of the mirror, and not in the stainless steel portion that contains the series connections. [Figure 10] The elements were switched to SOLID185 for a stress analysis. The long edges of the mirror were constrained in the direction normal to the mirror face, and free body constraints were added to the model. The moment resulting from the interaction of the currents and the toroidal field was 322N-m [2850in-lbf]. In future analyses, the boundary conditions will be changed to match the actual mirror supports. Stresses resulting from the electromagnetic loads are presented in figure 11. The maximum stress is 153MPa [22.2ksi]. This stress is localized at the tube/block interface, and can be reduced by adding fillets at the interface. In addition, an optimized mirror support can reduce this stress.

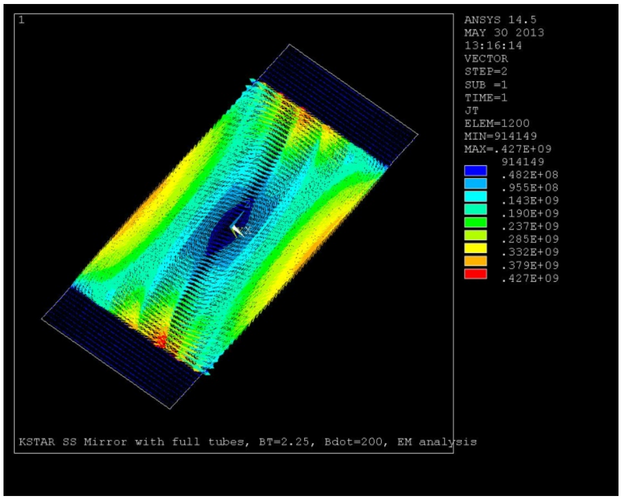

Fig. 10. Eddy Current Vector Plot

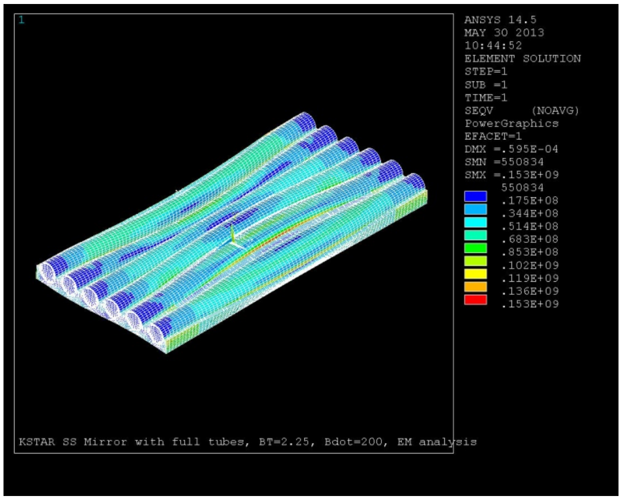

Fig. 11. Stresses due to Lorentz Forces

VII. CONCLUSIONS

A conceptual design for the KSTAR steady-state fixed mirror has been developed. Adequate performance and satisfactory stresses are obtained with a conservative set of design parameters. A first prototype has been built and tested successfully, and a second prototype has been designed. This prototype, with small modifications, will be the basis of a steady-state fixed mirror to be installed in the 170GHz launcher, where it will provide improved optics as well as long-pulse performance, for the 2014 KSTAR campaign. Some pre-conceptual steerable mirror designs are being evaluated. In the future, a new 2-beam steady-state launcher will be required to take full advantage of this new mirror technology.

ACKNOWLEDGMENT

This work was supported by the US DOE Contract No. DE-AC02-09CH11466.

REFERENCES

[1] Greenfield, C. M. et al, “Advanced Tokamak Research in DIII-D,” Physics of Plasmas 16(10), Article No. 102502, 2004

[2] Wagner, D. et al, “Recent Upgrades and Extensions of the ASDEX Upgrade ECRH System,” Journal of Infrared, Millimeter and Terahertz Waves, 32(3), pp.274-282, 2011

[3] Ikeda, Y. et al, “The 110GHz electron cyclotron range of frequency systemon JT60-U: Design and Operation,” Fusion Science and Technology 42(203), pp.435-451, 2002

[4] Volpe, F. et al, “Advanced Techniques for Neoclassical Tearing Mode Control in DIII-D,” Physics of Plasmas 16(10), Article Number 102502

[5] Murakami, M. et al, “Modification of the Current Profile in high-performance plasmas using off-axis electron cyclotron current drive,” Physical Review Letters 90(251), pp.2550011-2550014, 2003

[6] Ponce, D. et al, “Recent developments on the 110GHz electron cyclotron installation on the DIII-D tokamak, Fusion Engineering and Design 66-68, pp.521-524, 2003

[7] Bae, Y. S. et al, “Status of KSTAR Electron Heating System,” Fusion Science and Technology 52(2), pp. 321-333, 2007

[8] Bae, Y. S. et al, “Status of 170GHz, 1MW Electron Cyclotron Heating and Current Drive System, AIP Conference Proceedings 1406, pp. 177-1890, 2011

[9] Ellis, R. et al, “Development of high performance passively cooled mirrors for ECH launchers, “Proceedings, Symposium of Fusion Engineering, article No. 6052330, 2011

[10] Grant and Phillips, “Electromagnetism, 2nd edition,”, Wiley, 1990, pp.399-401

[11] Holman, J. P., “Heat Transfer, 4th edition,” McGraw-Hill, 1976, p. 206

[12] Ibid, p. 507

[13] Holman, op. cit., p. 209