Athermalization

In OSLO, air spaces are expanded by computing the thermal change in the corresponding edge thickness (defined at the aperture radius), and adding this change to the axial thickness. Note that this implies that the axial thickness itself does not affect the thermal expansion.

Radii of curvature are expanded according to the solid material bounding the radius, if the surface separates a solid and AIR. If a surface separates two solid materials, the average TCE of the two solids is used to expand the radius of curvature. This is obviously an ad hoc assumption, and for accurate thermal analysis, an extra surface should be used so that all solids are separated by AIR.

In the case of a mirror, OSLO uses the TCE of the following space to compute the thermal expansion. If the spacer in the following space is not made from the same material as the mirror, it is necessary to add an additional surface in contact with the mirror to accommodate the extra data.

The computation of thermal effects is fairly involved, partly because the data supplied by manufacturers are non-linear and not entirely consistent (e.g. some data are relative to air, and other data are relative to vacuum). One result of this is that it is not possible to exactly reverse a thermal change; there are residual round-off errors in the system parameters. While these are ordinarily not large enough to affect performance, it is a good idea to save a copy of the lens data prior to carrying out a thermal analysis.

The term *athermalization* refers to the process of making a lens insensitive to changes in temperature. When the temperature of the lens and its surroundings is changed, there are two effects that can be modeled by OSLO to account for their influence upon optical performance:

Thermal expansion - When temperature increases, all lengths in the optical system (radii of curvature, axial thicknesses, spacer thicknesses, aspheric and diffractive surface coefficients, and aperture radii) increase (approximately) proportionately, according to the value of the thermal expansion coefficient of each material. Thermal expansion coefficient values are provided in the Schott, Ohara, and Corning glass catalogs, and may be specified for individual glass or air spaces in lenses using the TCE command, as described above.

Thermal variation of refractive index - The refractive indices of optical materials (i.e. glasses) and of air vary with temperature; the index of air (and thus the relative indices of glasses) also varies with atmospheric pressure. Coefficients for the index vs. temperature relation are provided in the Schott glass catalog and can be specified for glasses added to the Private and Shared catalogs.

The temperature of the lens and its surroundings is set by using the **tem** command or by changing the Temperature value in the General Operating Conditions spreadsheet. The syntax of the **tem** command is: tem(*temperature, apply_thermal_expansion)*, where *temperature* is the temperature in degrees Celsius (default = 20 degrees, or room temperature), and *apply_thermal_expansion* is “Yes” to expand all lengths in the lens or “No” to leave the lengths unchanged. If the temperature is changed through the General Operating Conditions spreadsheet, thermal expansion is always applied. Refractive indices are always recomputed when the temperature is changed.

OSLO applies thermal expansion to lenses as follows. First, the radius of curvature, aspheric and diffractive coefficients, and aperture radius of each surface is expanded according to the expansion coefficient of the glass (i.e., non-air) side of the surface; cemented surfaces are expanded according to the average of the two expansion coefficients. Second, the (axial) thickness of each glass (i.e, non-air space) is expanded, also according to the expansion coefficient of the glass. Finally, air spaces are expanded by calculating the change in spacer thickness (which is taken to be the same as the edge thickness) and adding this change to the axial thickness; the expansion coefficient used is that of the spacer material (aluminum, by default).

To see the effect of temperature changes on the laser doublet, open the “public\len\demo\lt\lasrdblt.len” file and print the lens data. The last line of the OPERATING CONDITIONS: GENERAL section of the output shows the temperature in degrees Celsius; the default is 20 degrees, or room temperature. The REFRACTIVE INDICES section lists the glass (medium) for each surface and the value of the thermal expansion coefficient (TCE). Note that the refractive index of AIR is always given as 1.0, and that the TCE values of the air spaces is that of aluminum (236.0×10^{-7}).

```
*OPERATING CONDITIONS: GENERAL
   Temperature:              20.000000    Pressure:                  1.000000

*REFRACTIVE INDICES
 SRF     GLASS           RN1        TCE
  0      AIR          1.000000       --
  1      LASF35       2.014931   74.000000
  2      AIR          1.000000  236.000000
  3      LASF35       2.014931   74.000000
  4      AIR          1.000000  236.000000
  5      IMAGE SURFACE
```

Perform a paraxial analysis and note the Effective focal length and Image numerical aperture. Trace a spot diagram from the on-axis field point and note the Strehl ratio, which characterizes the performance of the system.

```
*PARAXIAL SETUP OF LENS
 APERTURE
   Entrance beam radius:     15.000000    Image axial ray slope:    -0.250000
   Object num. aperture:    1.5000e-19    F-number:                  2.000002
   Image num. aperture:       0.250000    Working F-number:          2.000002
.........
 OTHER DATA
   Entrance pupil radius:    15.000000    Srf 1 to entrance pup.:      --
   Exit pupil radius:        12.089964    Srf 4 to exit pupil:     -15.956128
   Lagrange invariant:     -1.5000e-05    Petzval radius:         -205.107372
   Effective focal length:   60.000049

*TRACE REFERENCE RAY
         FBY         FBX         FBZ
         --          --          --
        FYRF        FXRF         FY          FX
         --          --          --          --
         YC          XC          YFS         XFS         OPL    REF SPH RAD
         --          --       0.005766    0.005766   66.447315   48.354128


*SPOT DIAGRAM: MONOCHROMATIC
 APDIV    17.030000
 WAVELENGTH 1
 WAV WEIGHTS:
       WW1
    1.000000
 NUMBER OF RAYS TRACED:
       WV1
       232
 PER CENT WEIGHTED RAY TRANSMISSION:   100.000000

*SPOT SIZES
   GEO RMS Y   GEO RMS X   GEO RMS R  DIFFR LIMIT     CENTY       CENTX
    0.000490    0.000490    0.000692    0.001593      --          --

*WAVEFRONT RS
 WAVELENGTH 1
   PKVAL OPD     RMS OPD  STREHL RATIO    RSY         RSX         RSZ
    0.033080    0.011037    0.995412      --          --          --
```

Now apply change the temperature to 40 degrees and apply thermal expansion by issuing the command tem(40, yes) or by setting the Temperature to 40 in the General Operating Conditions spreadsheet. Print the lens data and compare the surface data and refractive indices to the original values. Perform a paraxial analysis and compare the new focal length and numerical aperture to the original values. Trace a spot diagram from the on-axis field point and compare the Strehl ratio to the original value.

```
*OPERATING CONDITIONS: GENERAL
   Temperature:              40.000000    Pressure:                  1.000000

*LENS DATA
He-ne f/2 doublet focusing lens
 SRF      RADIUS      THICKNESS   APERTURE RADIUS       GLASS SPE   NOTE
  0        --        1.0000e+20    1.0000e+14            AIR

  1     41.046074      5.000740     15.002220 A       LASF35 C
  2   -542.755316     13.906183     15.002220            AIR

  3    -40.701023      5.000740      9.001332         LASF35 P
  4   -124.330000     32.413446      9.000000            AIR
```

```
  5       --            --          0.002000

*REFRACTIVE INDICES
 SRF     GLASS           RN1       TCE
  1      LASF35        2.015019   74.000000
  2      AIR           1.000000  236.000000
  3      LASF35        2.015019   74.000000
.........

*PARAXIAL SETUP OF LENS
 APERTURE
   Entrance beam radius:     15.000000    Image axial ray slope:    -0.250029
   Object num. aperture:    1.5000e-19    F-number:                  1.999768
   Image num. aperture:       0.250029    Working F-number:          1.999768
.........
 OTHER DATA
   Entrance pupil radius:    15.000000    Srf 1 to entrance pup.:      --
   Exit pupil radius:        12.089353    Srf 4 to exit pupil:     -15.961051
   Lagrange invariant:     -1.5000e-05    Petzval radius:         -205.103693
   Effective focal length:   59.993027

*TRACE REFERENCE RAY
         FBY         FBX         FBZ
         --          --          --
        FYRF        FXRF          FY          FX
         --          --          --          --
         YC          XC          YFS         XFS         OPL    REF SPH RAD
         --          --       -0.022704   -0.022704   66.472804   48.374497

*SPOT DIAGRAM: MONOCHROMATIC
 APDIV    17.030000
 WAVELENGTH 1
 WAV WEIGHTS:
       WW1
    1.000000
 NUMBER OF RAYS TRACED:
       WV1
       232
 PER CENT WEIGHTED RAY TRANSMISSION:   100.000000

*SPOT SIZES
   GEO RMS Y   GEO RMS X   GEO RMS R  DIFFR LIMIT     CENTY       CENTX
    0.004227    0.004227    0.005978    0.001593      --          --

*WAVEFRONT RS
 WAVELENGTH 1
   PKVAL OPD     RMS OPD  STREHL RATIO    RSY         RSX         RSZ
    1.460707    0.434566    0.040493      --          --          --
```

In most cases, the effects of temperature change are limited to first-order; that is, changes in focal position and magnification. If the lens has a focusing mechanism, it can be used to counteract the temperature change (the focal shift is said to be a *compensator* for the temperature change). This can be seen here by using Autofocus and then re-tracing the on-axis spot diagram; the Strehl ratio should indicate that the system is once again well-corrected.

```
*AUTOFOCUS
Optimal focus shift =    -0.032475

*TRACE REFERENCE RAY
         FBY         FBX         FBZ
         --          --          --
        FYRF        FXRF          FY          FX
         --          --          --          --
         YC          XC          YFS         XFS         OPL    REF SPH RAD
         --          --        0.009771    0.009771   66.440329   48.342022

*SPOT DIAGRAM: MONOCHROMATIC
 APDIV    17.030000
 WAVELENGTH 1
 WAV WEIGHTS:
       WW1
    1.000000
 NUMBER OF RAYS TRACED:
       WV1
       232
 PER CENT WEIGHTED RAY TRANSMISSION:   100.000000

*SPOT SIZES
   GEO RMS Y   GEO RMS X   GEO RMS R  DIFFR LIMIT     CENTY       CENTX
    0.000594    0.000594    0.000841    0.001592      --          --

*WAVEFRONT RS
```

```
 WAVELENGTH 1
   PKVAL OPD     RMS OPD  STREHL RATIO    RSY         RSX         RSZ
    0.086983    0.019991    0.984163      --          --          --
```

In cases where no focusing mechanism is available, athermalization is considerably more difficult. It is necessary to choose materials (glass as well as mounts and spacers) carefully so that the effects of temperature change on one part of the lens are canceled by the effects on other parts of the lens.