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MacBurn's cylinder test problem

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`MacBurn`'s cylinder test problem *

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Abstract

This note describes test problem for `MacBurn` which illustrates its performance. The source is centered inside a cylinder with axial-extent-to-radius ratio s.t. each end receives 1/4 of the thermal energy. The source (fireball) is modeled as either a point or as disk of finite radius, as described by Marrs et al [2]. For the latter, the disk is divided into 13 equal area segments, each approximated as a point source and models a partially occluded fireball. If the source is modeled as a single point, one obtains very nearly the expected deposition, e.g., 1/4 of the flux on each end and energy is conserved. If the source is modeled as a disk, both conservation and energy fraction degrade. However, errors decrease if the source radius to domain size ratio decreases. Modeling the source as a disk increases run-times.

1 Test problem

This note accompanies the distribution of the computer code `MacBurn` that mpdels thermal energy deposition on a landscape/cityscape due to a nuclear airburst. We hope the note helps users understand what `MacBurn` does. Unless stated otherwise, all lengths are in meters.

An instructive example of `MacBurn`'s performance is found by computing its thermal energy deposition on the interior of a cylinder with radius R and axial extent Z. Using configuration factors, Siegel & Howell [3] p.849 #38, it can be shown that for the ratio $Z/R = \sqrt{4/3}$, if a diffuse spherical source is centered inside a cylinder, half the energy is deposited on the walls and one quarter on each of the ends.

To demonstrate `MacBurn`'s performance, `MacBurn`'s distribution contains an analogue of program `citify`, viz., the code `cylinder`, that constructs a cylin-

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drical domain. After generating the domain, `cityray` models thermal emission of a source inside. Once all programs are compiled, the cylindrical domain is generated as follows. Assuming one runs in a subdirectory, one level down from where the executables reside, the command:

```
../cylinder cylout i j k radius height kt  z0  flg
```

generates a cylindrical domain where

```
cylout (char) = name of the output model
i (int ) =  number of degrees per division in the mesh
j (int ) =  Number of divisions along radial axis; dR = rad/j
k (int ) =  Number of divisions (-1) along height; dZ = hit(k-1)
rad (dbl) = radius of cylinder (m)
hit (dbl or int) = axial extent of cylinder (m)
kt (dbl) = yield (kt)
z0 (dbl or int) = HOB (m)
flg (int) = 0 for non-linear, any other integer for linear
```

Thus,

```
../cylinder cylout 9 10 21 173.205 200 1.0 100 1
```

makes a cylinder of radius $R = 173.205$ and axial extent $Z = 200$. The azimuthal angle is discretized into segments of width 9 degrees (hence, 40 in all); the radial (axial) direction into 10 (20) uniform widths. The source energy is $Y = 1.0$ kt and is initially centered at $h = 100$ above the ground plane. The final argument `flg` allows nonuniform gridding. We always set it to 1 to get a uniform grid.

We perform three tests. The first two use the above domain. Test1 is run using the command

```
../cityray -command cmda -timings
```

where the input command file `cmda` is

```
input ../cylout.silo
output nucyl01
ndumps -10
xy 0.,0.
z0 100
yield 1.
zratemult 0.0
method raytrace
# use new power function
PowerFun 1
RadiusTime 0.0
```

Thus, the test models a *point* source (`method raytrace`) centered in the cylinder; the source strength, `yield` = 1 kt (10^{12} cal.) Ten nonuniform time steps (`ndumps -10`) emit approximately the same energy. Total emitted energy should be 80% of the yield times the thermal partition (35%), i.e, $0.28 \cdot 10^{12}$ cal, Glasstone and Dolan [1]. The source is stationary (`zratemult 0.`) For this problem, parameter `RadiusTime` is redundant since the source is modeled as a point.

2 Results

Results are analyzed using `VisIt`. We should expect errors of at least 0.25% since the domain is not a true cylinder due to discretization. The ratio of areas of a true cylinder to the numerical domain is

```
4.0615e+05/4.0515e+05 = 1.0025
```

The sum of the total energy deposited is $0.278718 \cdot 10^{12}$ cal, which gives a relative error of 2.8/2.78718 - 1. = 0.0046, i.e., less than 0.5%. Lastly, the sum of the energy deposited on each end is $0.0695719 \cdot 10^{12}$ cal. Hence, each end receives 0.0695719/0.278718 = 0.2496 instead of 0.25, i.e., a 0.16% error. Given the coarseness of the discretization, results are excellent

For Test2, the above `command` file is modified; `method raytrace` is replaced with `raytrace_disk`, i.e., instead of a point, the source is modeled as a stationary disk of radius 30 m, as described in Marrs et al [2]. The disk radius is fixed since `RadiusTime 0.` For this case, the sum of the total energy deposited is $0.257818 \cdot 10^{12}$ cal, which gives a relative error of 2.8/2.57818 - 1. = 0.086, i.e., 8.6%. (We discuss the 8.6% error at the conclusion of Section 3.) The sum of the energy deposited on each end is $0.0628724 \cdot 10^{12}$ cal. Hence, each end receives 0.0628724/0.257818 = 0.2439 instead of 0.25, i.e., a 2.5% error.

The Test2 results for total energy, illustrate a “feature” of the Marrs et al scheme that approximates a sphere with a disk. A disk is a good approximation to a sphere of the same radius *if* the source is far from the absorbing surface. However, for a surface near the source, the approximation degrades. The effect is similar to a person standing on the earth’s surface; she cannot see beyond the horizon, a distance is significantly less than the earth’s radius.

In the above tests, the domain size implies that a true spherical source (of radius 30 m) would have its edge only 70 m from each end. Hence, the edge centers should “see” a disk of smaller radius, viz., 28.19 m. But, if the source radius is kept fixed at 30 m and the domain dimensions increased, the disk approximation should improve.

To confirm the hypotheses, we run Test3 in which we double the dimensions and increase resolution by calling `cylinder` using

```
../cylinder cylout 3 20 41 346.41 400 1.0 200 1
```

We run as for Test2, except now center the source at $z = 200$. In this case, the domain area agrees with the true area to five digits: $1.6242 \cdot 10^6$ vs. $1.6246 \cdot 10^6$. Now, the sum of the total energy deposited is $0.273095 \cdot 10^{12}$ cal, which gives a relative error of 2.8/2.73095 - 1. = 0.0253, i.e., 2.5% instead of 8.6%, as in Test2. Also, the sum of the energy deposited on each end is $0.0678336 \cdot 10^{12}$ cal. Hence, each end receives $0.0678336/0.273095 = 0.2484$ instead of 0.25, i.e., a 0.6% error instead of the 2.5% error in Test2.

3 Timings, summary

If `cityray` is run using the option `timings`, a separate outfile `cityray.timings` displays the time (in sec) for various code processes. The file's last line shows how much time the main loop took. From the respective files:

```
Test1:Main loop took 0.876718
Test2:Main loop took 12.117986
Test3:Main loop took 220.167262
```

The ratio of Test2/Test1 equals 13.822 and is expected. Test2 models the fireball as a disk divided into 13 separate equal area point sources.

The Test3/Test2 ratio equals 18.1686 and is larger than one would at first expect. Test2 and Test3 discretize the domain into 3120 and 18960, resp., i.e., Test3 has 6.08 more triangles than Test2. Naively one would expect only 6$\times$ more work. For this simple example, that is true since every boundary triangle "sees" the entire disk. However, that is not the case in general since the ray-trace algorithm follows a tree-like structure to determine if the line joining source to triangle is not blocked by another triangle, as would be the case if one structure shadows another. Thus, the 18-fold increase is due to two processes. One is a 6-fold increase due to the number of boundary triangles. Another is a 3-fold increase due to traversing a larger tree structure.

We conclude with two comments. One pertains to the ratio of the expected total energy deposited vs. the expected value: 80% $\times$ thermal partition $\times$ yield. The simulations were done using only 10 (nonuniform) time steps that integrated over the Power(time) curve. Hence, some error should be expected.

The second comment explains the source of the 8.6% error for the total emitted energy in Test2. In method `raytrace_disk`, the energy deposited on triangles is computed as follows. For each triangle, the fireball is approximated as a disk co-centered with the fireball. The disk is oriented so its normal points to the triangle center. The disk is divided into 13 equal area patches (subsources), each modeled as a point source located at the subsource center. Each subsource is a diffuse source with strenth equal to 1/13 of the total. Each subsource deposits energy based on the solid angle it generates that envelops the triangle in question. However, the solid angles for each subsource may differ, and significantly so, for triangles near the source. Hence, the sum of energy deposited by the subsources need not equal the energy deposited by a single point source at the fireball center. The error is significantly reduced for triangles far from the source, as shown in the results for Test3 vs. Test2.

References

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[3] R. Siegel and J. R. Howell, *Thermal Radiation Heat Transfer,* Fourth Edition, Taylor & Francis, New York, 2002