《基于openEuler的openlb软件测试报告》

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1. 规范性自检

项目使用了Artistic Style对文件进行格式化

Artistic Style（AStyle）是一个可用于C, C++, Objective-C, C#和Java编程语言格式化和美化的工具。由于各个用户、项目程序编写规范存在差异，各个编辑器对缩进、换行等的标准不同，项目代码的格式化和规范、美化有助于代码阅读和协作。AStyle可以对项目代码进行格式化和美化，并提供了高度可自定义的配置文件和方法更好地规范代码。

文件格式化样式参考google代码风格，配置文件`config.ini`内容如下：

```
# Google Coding Style Options
# braces and indent
style=google
indent=spaces=2
# indentation
indent-switches
indent-continuation=2
indent-preproc-define
min-conditional-indent=0
max-continuation-indent=80
# padding
pad-oper
pad-header
unpad-paren
align-pointer=type
# formatting
break-one-line-headers
keep-one-line-blocks
keep-one-line-statements
convert-tabs
# objective-c
pad-method-prefix
unpad-return-type
unpad-param-type
align-method-colon
pad-method-colon=none
```

对于当前项目，检查代码规范性，可以通过使用AStyle对所有源码进行重新格式化，然后使用git工具查看文件修改。

1.1 选择统计文件类型

统计项目文件类型及其文件数量，通过Python脚本自动进行统计并进行排序：

```python
# -*- coding: utf-8 -*-

import os

me = __file__
print("分析文件夹：" + os.getcwd())

def getAllFiles(targetDir):
    files = []
    listFiles = os.listdir(targetDir)
    for file in listFiles:
        path = os.path.join(targetDir, file)
        if os.path.isdir(path):
            files.extend(getAllFiles(path))
        elif os.path.isfile(path) and path != me:
            files.append(path)
```

```
    return files

all_files=getAllFiles(os.curdir)
type_dict=dict()

for file in all_files:
    if os.path.isdir(file):
        type_dict.setdefault("文件夹", 0)
        type_dict["文件夹"]+=1
    else:
        ext=os.path.splitext(file)[1]
        type_dict.setdefault(ext, 0)
        type_dict[ext]+=1

type_dict["空"] = type_dict.pop("")
sort_dict = sorted(type_dict.items(), key = lambda a: a[1], reverse = True)

for each_type in sort_dict:
    print("当前文件夹下共有后缀名为【%s】的文件%d个" %(each_type[0], each_type[1]))
```

在OpenLB项目根目录下运行，得到统计结果如下（排除自身）：

```
分析文件夹：D:\Git\PortOpenLB\package\olb-1.4r0
当前文件夹下共有后缀名为【.h】的文件512个
当前文件夹下共有后缀名为【.hh】的文件428个
当前文件夹下共有后缀名为【.cpp】的文件265个
当前文件夹下共有后缀名为【.mk】的文件101个
当前文件夹下共有后缀名为【空】的文件61个
当前文件夹下共有后缀名为【.c】的文件15个
当前文件夹下共有后缀名为【.xml】的文件8个
当前文件夹下共有后缀名为【.dsp】的文件5个
当前文件夹下共有后缀名为【.vcproj】的文件4个
当前文件夹下共有后缀名为【.nix】的文件3个
当前文件夹下共有后缀名为【.stl】的文件3个
当前文件夹下共有后缀名为【.sh】的文件3个
当前文件夹下共有后缀名为【.inp】的文件3个
当前文件夹下共有后缀名为【.py】的文件2个
当前文件夹下共有后缀名为【.txt】的文件2个
当前文件夹下共有后缀名为【.hpp】的文件2个
当前文件夹下共有后缀名为【.fcstd】的文件1个
当前文件夹下共有后缀名为【.p】的文件1个
当前文件夹下共有后缀名为【.dsw】的文件1个
当前文件夹下共有后缀名为【.sln】的文件1个
当前文件夹下共有后缀名为【.gif】的文件1个
```

主要源码文件后缀名为`h`，`hh`，`cpp`以及部分C语言文件。由此判断该项目主要语言为C++/C。

1.2 统计源码代码量

统计行数：

```
find ./ -regex ".*\.hpp\|.*\.h\|.*\.cpp|.*\.c|.*\.hh" | xargs wc -l
```

行数统计后结果输出如下：

```
67334 total
```

统计字数：

```
find ./ -regex ".*\.hpp\|.*\.h\|.*\.cpp|.*\.c|.*\.hh" | xargs wc -m
```

字数统计后结果输出如下：

```
2517196 total
```

1.3 统计不符合要求的总行数

对源代码文件（后缀名为`cpp`，`hpp`，`h`，`hh`，`c`）进行AStyle代码样式格式化，格式化结果如下：

```
royenheart@LAPTOP-TDKNUURL:/mnt/d/Git/PortOpenLB/package/olb-1.4r0$ astyle --
project=styles/google.ini -R ./*.cpp,*.c,*.h,*.hh,*.hpp -Qnv
Artistic Style 3.1                                  08/29/2022
Project option file  /mnt/d/Git/PortOpenLB/package/olb-1.4r0/styles/google.ini
------------------------------------------------------------
Directory  ./*.cpp,*.c,*.h,*.hh,*.hpp
------------------------------------------------------------
Formatted  examples/laminar/bstep2d/bstep2d.cpp
Formatted  examples/laminar/bstep3d/bstep3d.cpp
Formatted  examples/laminar/cavity2d/cavity2d.cpp
Formatted  examples/laminar/cavity3d/cavity3d.cpp
Formatted  examples/laminar/cylinder2d/cylinder2d.cpp
Formatted  examples/laminar/cylinder3d/cylinder3d.cpp
Formatted  examples/laminar/poiseuille2d/poiseuille2d.cpp
Formatted  examples/laminar/poiseuille3d/poiseuille3d.cpp
Formatted  examples/laminar/powerLaw2d/powerLaw2d.cpp
Formatted  examples/multiComponent/contactAngle2d/contactAngle2d.cpp
.........（篇幅过长不详细列举）
------------------------------------------------------------
 1,032 formatted   190 unchanged   2.6 seconds   203,326 lines
```

使用git工具对文件格式化后的修改内容进行统计：

```
royenheart@LAPTOP-TDKNUURL:/mnt/d/Git/PortOpenLB/package/olb-1.4r0$ git commit -m
"openlb format"
[master cfbf5ca] openlb format
 1032 files changed, 52268 insertions(+), 58634 deletions(-)
 rewrite examples/multiComponent/microFluidics2d/microFluidics2d.cpp (66%)
 rewrite examples/particles/bifurcation3d/eulerEuler/bifurcation3d.cpp (64%)
 rewrite examples/particles/bifurcation3d/eulerLagrange/bifurcation3d.cpp (64%)
 rewrite examples/thermal/galliumMelting2d/galliumMelting2d.cpp (74%)
 rewrite examples/thermal/stefanMelting2d/stefanMelting2d.cpp (74%)
 rewrite src/boundary/setBoundaryCondition2D.cpp (75%)
 rewrite src/boundary/setBoundaryCondition3D.cpp (69%)
 rewrite src/dynamics/freeEnergyPostProcessor2D.hh (70%)
 rewrite src/dynamics/freeEnergyPostProcessor3D.hh (78%)
 rewrite src/dynamics/mrtHelpers2D.h (61%)
 rewrite src/dynamics/mrtHelpers3D.h (81%)
 rewrite src/external/tinyxml/tinyxml.cpp (60%)
 rewrite src/external/zlib/adler32.c (65%)
 rewrite src/external/zlib/deflate.c (75%)
 rewrite src/external/zlib/deflate.h (66%)
 rewrite src/external/zlib/gzlib.c (79%)
 rewrite src/external/zlib/gzread.c (78%)
 rewrite src/external/zlib/gzwrite.c (85%)
 rewrite src/external/zlib/infback.c (77%)
 rewrite src/external/zlib/inffast.c (76%)
 rewrite src/external/zlib/inffixed.h (99%)
 rewrite src/external/zlib/inflate.c (71%)
 rewrite src/external/zlib/inflate.h (72%)
 rewrite src/external/zlib/inftrees.c (87%)
 rewrite src/external/zlib/trees.c (70%)
 rewrite src/external/zlib/trees.h (96%)
 rewrite src/functors/analytical/analyticalF.cpp (68%)
 rewrite src/functors/lattice/integral/superPlaneIntegralFluxF2D.cpp (70%)
 rewrite src/functors/lattice/integral/superPlaneIntegralFluxF3D.cpp (83%)
 rewrite src/functors/lattice/latticeFrameChangeF3D.hh (60%)
```

1.4 统计结果

综上信息，项目中代码规范性自检检查结果为:

通过率：

$$12.92\% = \frac{67334 - 58634}{67334} * 100\%$$

不通过率：

$$87.08\% = \frac{58634}{67334} * 100\%$$

2. 功能性测试

2.1 测试案例

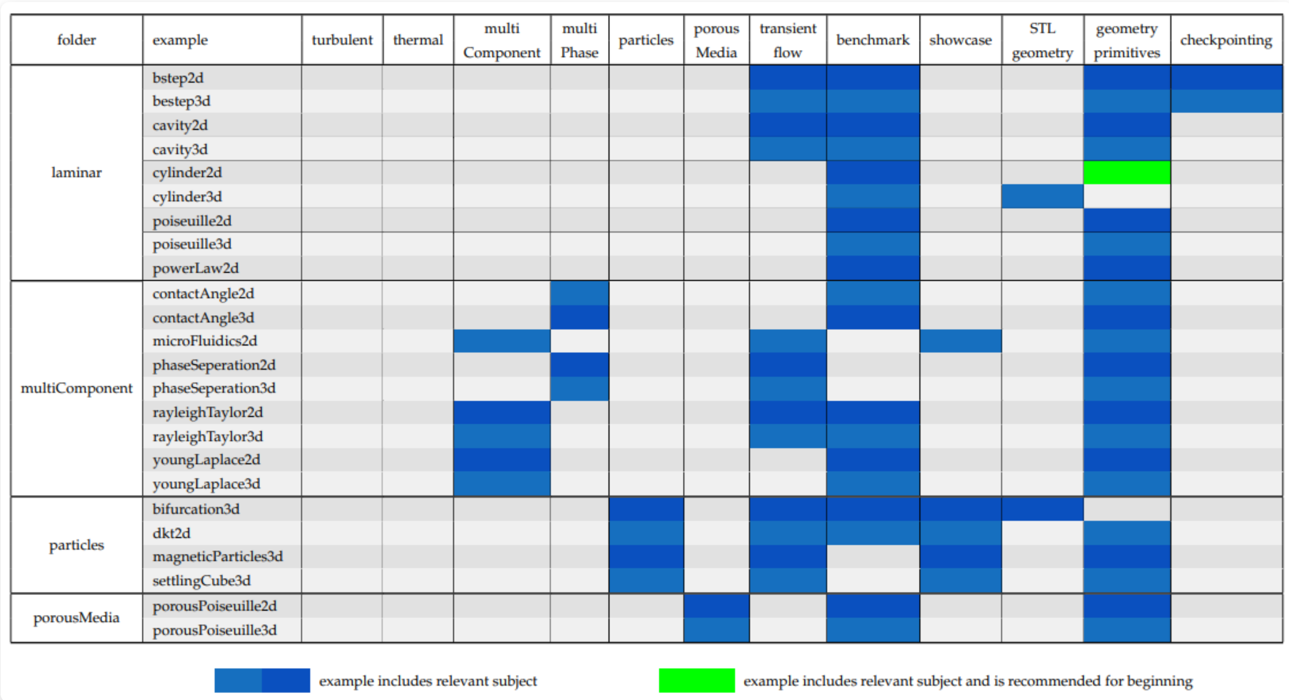
OpenLB针对流体力学不同领域和情况在项目中提供了各种仿真实验测试文件，可以使用这些单元测试文件了解入门流体力学相关实验和对项目正确性进行验证。

单元测试文件数如下：

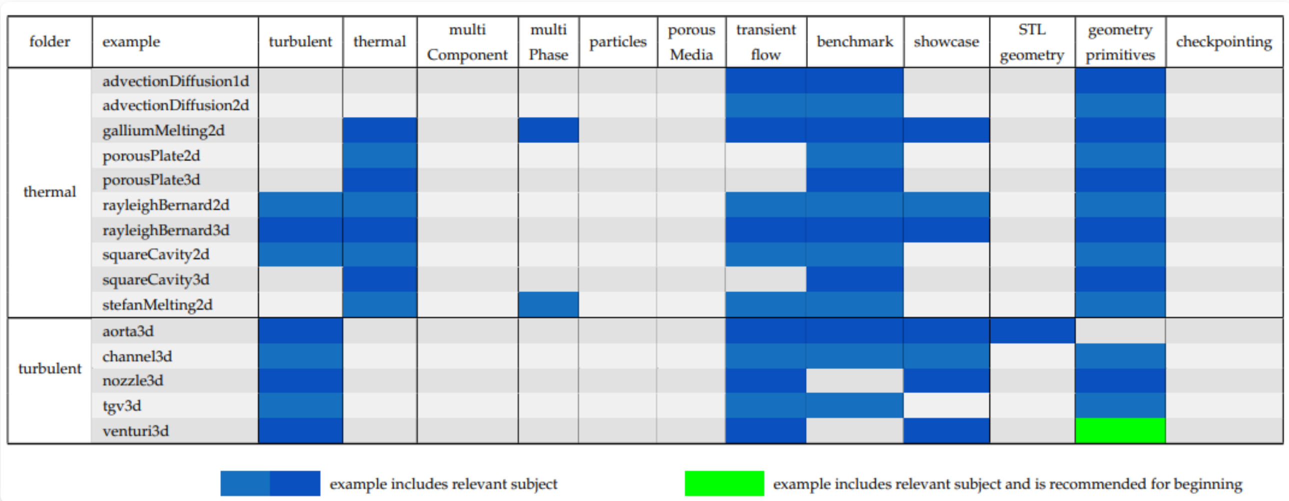
```
olb-1.4r0/examples
├─laminar
│  ├─bstep2d
│  ├─bstep3d
│  ├─cavity2d
│  ├─cavity3d
│  ├─cylinder2d
│  ├─cylinder3d
│  ├─poiseuille2d
│  ├─poiseuille3d
│  └─powerLaw2d
├─multiComponent
│  ├─contactAngle2d
│  ├─contactAngle3d
│  ├─microFluidics2d
│  ├─phaseSeparation2d
│  ├─phaseSeparation3d
│  ├─rayleighTaylor2d
│  ├─rayleighTaylor3d
│  ├─youngLaplace2d
│  └─youngLaplace3d
├─particles
│  ├─bifurcation3d
│  │  ├─eulerEuler
│  │  └─eulerLagrange
│  ├─dkt2d
│  ├─magneticParticles3d
│  └─settlingCube3d
├─porousMedia
│  ├─porousPoiseuille2d
│  └─porousPoiseuille3d
├─thermal
│  ├─advectionDiffusion1d
│  ├─advectionDiffusion2d
│  ├─galliumMelting2d
│  ├─porousPlate2d
│  ├─porousPlate3d
│  ├─rayleighBenard2d
│  ├─rayleighBenard3d
│  ├─squareCavity2d
│  ├─squareCavity3d
│  └─stefanMelting2d
└─turbulence
    ├─aorta3d
    ├─channel3d
    ├─nozzle3d
```

```
    ├─tgv3d
    └─venturi3d
```

案例测试程序对应流体力学测试方向如下：



程序列表1



程序列表2

2.2 功能测试

OpenLB仅作为一个框架，只生成对应的库文件和头文件，而在examples目录中提供了各种方向的测试程序，需要用户在编译后自行进入各个测试案例目录运行。部分测试程序需要外部输入文件，OpenLB已在对应目录提供。

由于所有案例程序调用的都是OpenLB的框架（链接到库），因此只测试部分程序查看OpenLB框架的正确性。这里以**porousPoiseuille3d**和**contactAngle2d**两个程序进行测试，二者可覆盖olb框架对2d和3d情况的仿真模拟。

```
# 进入项目根目录并配置好编译参数后（在config.mk文件中指定）对OpenLB框架和各个测试案例进行编译
make samples -j
```

- 进行测试

```
# 测试命令
#!/bin/bash

testFile=$1

export OMP_NUM_THREADS=24
export OMP_PROC_BIND=true
export OMP_PLACES=cores

mpirun -machinefile nodes -np 12 -npernode 4 --bind-to numa --mca btl
^vader,tcp,openib \
    --map-by numa --rank-by numa \
    -x UCX_TLS=sm,ud_x -x UCX_NET_DEVICES=mlx5_0:1 \
    -x UCX_BUILTIN_BCAST_ALGORITHM=3 \
    -x UCX_BUILTIN_ALLREDUCE_ALGORITHM=6 \
    -x UCX_BUILTIN_BARRIER_ALGORITHM=5 \
    -x UCX_BUILTIN_DEGREE_INTRA_FANOUT=3 \
    -x UCX_BUILTIN_DEGREE_INTRA_FANIN=2 \
    -x UCX_BUILTIN_DEGREE_INTER_FANOUT=7 \
    -x UCX_BUILTIN_DEGREE_INTER_FANIN=7 \
    ${testFile}
```

- 测试结果（porousPoiseuille3d）

```
Warning: Permanently added 'n2,192.168.0.3' (ECDSA) to the list of known hosts.
Warning: Permanently added 'n3,192.168.0.4' (ECDSA) to the list of known hosts.
[MpiManager] Sucessfully initialized, numThreads=12
[[[[[[OmpManager] [[[OmpManager] [[[OmpManager] OmpManager] OmpManager]
OmpManagerOmpManager] ] [OmpManager] Sucessfully initialized, numThreads=24
OmpManager] [Sucessfully initialized, numThreads=24
Sucessfully initialized, numThreads=24
Sucessfully initialized, numThreads=24
Sucessfully initialized, numThreads=24
Sucessfully initialized, numThreads=24
Sucessfully initialized, numThreads=24
OmpManager] Sucessfully initialized, numThreads=24
OmpManager] OmpManager] [Sucessfully initialized, numThreads=24
OmpManager] [OmpManager] Sucessfully initialized, numThreads=24
Sucessfully initialized, numThreads=24
Sucessfully initialized, numThreads=24
OmpManagerSucessfully initialized, numThreads=24
[OmpManager] OmpManager] Sucessfully initialized, numThreads=24
```

```
Sucessfully initialized, numThreads=24
] [OmpManager] Sucessfully initialized, numThreads=24
Sucessfully initialized, numThreads=24
Sucessfully initialized, numThreads=24
[OmpManager] Sucessfully initialized, numThreads=24
[OmpManager] Sucessfully initialized, numThreads=24
[OmpManager] Sucessfully initialized, numThreads=24
[OmpManager] Sucessfully initialized, numThreads=24
[OmpManager] Sucessfully initialized, numThreads=24
[OmpManager] Sucessfully initialized, numThreads=24
[prepareGeometry] Prepare Geometry ...
[SuperGeometry3D] cleaned 4104 outer boundary voxel(s)
[SuperGeometry3D] cleaned 0 inner boundary voxel(s)
[SuperGeometry3D] the model is correct!
[CuboidGeometry3D] ---Cuboid Stucture Statistics---
[CuboidGeometry3D]  Number of Cuboids:  24
[CuboidGeometry3D]  Delta  (min):       0.047619
[CuboidGeometry3D]         (max):       0.047619
[CuboidGeometry3D]  Ratio  (min):       0.636364
[CuboidGeometry3D]         (max):       1.71429
[CuboidGeometry3D]  Nodes  (min):       847
[CuboidGeometry3D]         (max):       1056
[CuboidGeometry3D]  Weight (min):       660
[CuboidGeometry3D]         (max):       1056
[CuboidGeometry3D] --------------------------------
[SuperGeometryStatistics3D] materialNumber=0; count=3060; minPhysR=
(-0.047619,0,0); maxPhysR=(2.04762,1,1)
[SuperGeometryStatistics3D] materialNumber=1; count=14276; minPhysR=
(0,0.047619,0.047619); maxPhysR=(2,0.952381,0.952381)
[SuperGeometryStatistics3D] materialNumber=2; count=3780; minPhysR=
(-0.047619,0,0); maxPhysR=(2.04762,1,1)
[SuperGeometryStatistics3D] materialNumber=3; count=332; minPhysR=
(-0.047619,0.047619,0.047619); maxPhysR=(-0.047619,0.952381,0.952381)
[SuperGeometryStatistics3D] materialNumber=4; count=332; minPhysR=
(2.04762,0.047619,0.047619); maxPhysR=(2.04762,0.952381,0.952381)
[prepareGeometry] Prepare Geometry ... OK
[prepareLattice] Prepare Lattice ...
[prepareLattice] Lattice Porosity: 0.981859
[prepareLattice] Kmin: 0.000181406
[prepareLattice] Prepare Lattice ... OK
[main] starting simulation...
[Timer] step=0; percent=0; passedTime=1.252; remTime=110425; MLUPs=0
[LatticeStatistics] step=0; t=0; uMax=0.000733084; avEnergy=1.4351e-07;
avRho=1.00106
[SuperPlaneIntegralFluxVelocity3D] regionName=Inflow; regionSize[m^2]=0.589569;
volumetricFlowRate[m^3/s]=0.0739175; meanVelocity[m/s]=0.125375
[SuperPlaneIntegralFluxPressure3D] regionName=Inflow; regionSize[m^2]=0.589569;
force[N]=18.7033; meanPressure[Pa]=31.7237
[SuperPlaneIntegralFluxVelocity3D] regionName=Outflow; regionSize[m^2]=0.664399;
volumetricFlowRate[m^3/s]=0.0770278; meanVelocity[m/s]=0.115936
[SuperPlaneIntegralFluxPressure3D] regionName=Outflow; regionSize[m^2]=0.664399;
force[N]=-0.0626416; meanPressure[Pa]=0.0942832
[getResults] pressure1=16.3205; pressure2=15.6805; pressureDrop=0.64
[error] velocity-L1-error(abs)=0.00819255; velocity-L1-error(rel)=0.0496816
```

```
[error] velocity-L2-error(abs)=0.00950415; velocity-L2-error(rel)=0.0671756
[error] velocity-Linf-error(abs)=0.0377358; velocity-Linf-error(rel)=0.245121
[error] pressure-L1-error(abs)=0.730704; pressure-L1-error(rel)=0.029626
[error] pressure-L2-error(abs)=1.17404; pressure-L2-error(rel)=0.0508801
[error] pressure-Linf-error(abs)=3.89607; pressure-Linf-error(rel)=0.121752
[ValueTracer] average=1.47662e-07; stdDev/average=0.0138736
[main] Simulation converged.
[Timer] step=1570; percent=1.78005; passedTime=4.495; remTime=248.027;
MLUPs=9.06272
[LatticeStatistics] step=1570; t=0.356009; uMax=0.000772759; avEnergy=1.48448e-07;
avRho=1.0011
[SuperPlaneIntegralFluxVelocity3D] regionName=Inflow; regionSize[m^2]=0.589569;
volumetricFlowRate[m^3/s]=0.0744295; meanVelocity[m/s]=0.126244
[SuperPlaneIntegralFluxPressure3D] regionName=Inflow; regionSize[m^2]=0.589569;
force[N]=19.2009; meanPressure[Pa]=32.5677
[SuperPlaneIntegralFluxVelocity3D] regionName=Outflow; regionSize[m^2]=0.664399;
volumetricFlowRate[m^3/s]=0.0790515; meanVelocity[m/s]=0.118982
[SuperPlaneIntegralFluxPressure3D] regionName=Outflow; regionSize[m^2]=0.664399;
force[N]=-0.166278; meanPressure[Pa]=0.250269
[getResults] pressure1=16.4704; pressure2=15.8142; pressureDrop=0.656244
[error] velocity-L1-error(abs)=0.00501721; velocity-L1-error(rel)=0.0304256
[error] velocity-L2-error(abs)=0.00417934; velocity-L2-error(rel)=0.0295397
[error] velocity-Linf-error(abs)=0.0177805; velocity-Linf-error(rel)=0.115497
[error] pressure-L1-error(abs)=0.356608; pressure-L1-error(rel)=0.0144585
[error] pressure-L2-error(abs)=0.352035; pressure-L2-error(rel)=0.0152564
[error] pressure-Linf-error(abs)=1.13082; pressure-Linf-error(rel)=0.035338
[Timer]
[Timer] ----------------Summary:Timer----------------
[Timer] measured time (rt) : 5.200s
[Timer] measured time (cpu): 61.404s
[Timer] average MLUPs :       5.652
[Timer] average MLUPps:       0.020
[Timer] ---------------------------------------------
```

- 测试结果（contactAngle2d）

```
Warning: Permanently added 'n2,192.168.0.3' (ECDSA) to the list of known hosts.
Warning: Permanently added 'n3,192.168.0.4' (ECDSA) to the list of known hosts.
[MpiManager] Sucessfully initialized, numThreads=12
[[[[OmpManager] [[[OmpManager] [[[OmpManager] OmpManager] OmpManagerSucessfully
initialized, numThreads=24
[OmpManager] [OmpManager] Sucessfully initialized, numThreads=24
] [OmpManager] [Sucessfully initialized, numThreads=24
Sucessfully initialized, numThreads=24
Sucessfully initialized, numThreads=24
Sucessfully initialized, numThreads=24
[OmpManager] [OmpManager] Sucessfully initialized, numThreads=24
OmpManager] [Sucessfully initialized, numThreads=24
OmpManager] Sucessfully initialized, numThreads=24
[OmpManager] OmpManager] Sucessfully initialized, numThreads=24
[OmpManager] Sucessfully initialized, numThreads=24
OmpManager] [OmpManager] Sucessfully initialized, numThreads=24
```

```
Sucessfully initialized, numThreads=24
Sucessfully initialized, numThreads=24
OmpManager] OmpManager] Sucessfully initialized, numThreads=24
OmpManager] Sucessfully initialized, numThreads=24
Sucessfully initialized, numThreads=24
Sucessfully initialized, numThreads=24
[OmpManager] Sucessfully initialized, numThreads=24
Sucessfully initialized, numThreads=24
Sucessfully initialized, numThreads=24
[OmpManager] Sucessfully initialized, numThreads=24
[OmpManager] Sucessfully initialized, numThreads=24
[OmpManager] Sucessfully initialized, numThreads=24
[UnitConverter] ----------------- UnitConverter information -----------------
[UnitConverter] -- Parameters:
[UnitConverter] Resolution:                         N=              75
[UnitConverter] Lattice velocity:                   latticeU=       1663.34
[UnitConverter] Lattice relaxation frequency:       omega=          1
[UnitConverter] Lattice relaxation time:            tau=            1
[UnitConverter] Characteristical length(m):         charL=          75
[UnitConverter] Characteristical speed(m/s):        charU=          0.0001
[UnitConverter] Phys. kinematic viscosity(m^2/s): charNu=           1.002e-08
[UnitConverter] Phys. density(kg/m^d):              charRho=        1
[UnitConverter] Characteristical pressure(N/m^2): charPressure=     0
[UnitConverter] Mach number:                        machNumber=     2880.99
[UnitConverter] Reynolds number:                    reynoldsNumber= 748503
[UnitConverter] Knudsen number:                     knudsenNumber=  0.003849
[UnitConverter]
[UnitConverter] -- Conversion factors:
[UnitConverter] Voxel length(m):                    physDeltaX=     1
[UnitConverter] Time step(s):                       physDeltaT=     1.66334e+07
[UnitConverter] Velocity factor(m/s):               physVelocity=   6.012e-08
[UnitConverter] Density factor(kg/m^3):             physDensity=    1
[UnitConverter] Mass factor(kg):                    physMass=       1
[UnitConverter] Viscosity factor(m^2/s):            physViscosity=  6.012e-08
[UnitConverter] Force factor(N):                    physForce=      3.61441e-15
[UnitConverter] Pressure factor(N/m^2):             physPressure=   3.61441e-15
[UnitConverter] -------------------------------------------------------------
[LoadBalancer] glob[0]=0
[LoadBalancer] loc[0]=0
[LoadBalancer] rank[0]=0
[LoadBalancer] rank[1]=1
[LoadBalancer] rank[2]=2
[LoadBalancer] rank[3]=3
[LoadBalancer] rank[4]=4
[LoadBalancer] rank[5]=5
[LoadBalancer] rank[6]=6
[LoadBalancer] rank[7]=7
[LoadBalancer] rank[8]=8
[LoadBalancer] rank[9]=9
[LoadBalancer] rank[10]=10
[LoadBalancer] rank[11]=11
[prepareGeometry] Prepare Geometry ...
[SuperGeometry2D] cleaned 0 inner boundary voxel(s)
[SuperGeometry2D] the model is correct!
```

```
[CuboidGeometry2D] ---Cuboid Stucture Statistics---
[CuboidGeometry2D]  Number of Cuboids:  12
[CuboidGeometry2D]  Delta (min):        1
[CuboidGeometry2D]        (max):        1
[CuboidGeometry2D]  Ratio (min):        1
[CuboidGeometry2D]        (max):        1.11765
[CuboidGeometry2D]  Nodes (min):        323
[CuboidGeometry2D]        (max):        323
[CuboidGeometry2D] --------------------------------
[SuperGeometryStatistics2D] materialNumber=1; count=3724; minPhysR=(0,1);
maxPhysR=(75,49)
[SuperGeometryStatistics2D] materialNumber=2; count=152; minPhysR=(0,0); maxPhysR=
(75,50)
[prepareGeometry] Prepare Geometry ... OK
[prepareLattice] Prepare Lattice ...
[prepareLattice] Prepare Lattice ... OK
[prepareCoupling] Add lattice coupling
[prepareCoupling] Add lattice coupling ... OK!
[main] starting simulation...
[Timer] step=0; percent=0; passedTime=0.724; remTime=50679.3; MLUPs=0
[LatticeStatistics] step=0; t=0; uMax=0; avEnergy=0; avRho=1
[LatticeStatistics] step=0; t=0; uMax=0; avEnergy=0; avRho=1
[getResults] ----->>>>> Contact angle: 89.9697 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: -0.03031
[Timer] step=1000; percent=1.42857; passedTime=1.482; remTime=102.258;
MLUPs=5.10672
[LatticeStatistics] step=1000; t=1.66334e+10; uMax=0.000147109; avEnergy=7.93412e-
10; avRho=1
[LatticeStatistics] step=1000; t=1.66334e+10; uMax=0.000147109; avEnergy=7.93412e-
10; avRho=0.709499
[getResults] ----->>>>> Contact angle: 90.4014 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.431718
[Timer] step=2000; percent=2.85714; passedTime=2.253; remTime=76.602;
MLUPs=5.02724
[LatticeStatistics] step=2000; t=3.32668e+10; uMax=0.000134568; avEnergy=9.72497e-
10; avRho=1
[LatticeStatistics] step=2000; t=3.32668e+10; uMax=0.000134568; avEnergy=9.72497e-
10; avRho=0.709499
[getResults] ----->>>>> Contact angle: 91.1413 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.739916
[Timer] step=3000; percent=4.28571; passedTime=3.002; remTime=67.0447; MLUPs=5.168
[LatticeStatistics] step=3000; t=4.99002e+10; uMax=0.00012501; avEnergy=9.61883e-
10; avRho=1
[LatticeStatistics] step=3000; t=4.99002e+10; uMax=0.00012501; avEnergy=9.61883e-
10; avRho=0.709498
[getResults] ----->>>>> Contact angle: 91.8496 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.70832
[Timer] step=4000; percent=5.71429; passedTime=4.379; remTime=72.2535;
MLUPs=2.81686
[LatticeStatistics] step=4000; t=6.65336e+10; uMax=0.000115249; avEnergy=9.0075e-
10; avRho=1
[LatticeStatistics] step=4000; t=6.65336e+10; uMax=0.000115249; avEnergy=9.0075e-
10; avRho=0.709498
[getResults] ----->>>>> Contact angle: 92.529 ; Analytical contact angle: 100.001
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[getResults] ----->>>>> Difference to previous: 0.679393
[Timer] step=5000; percent=7.14286; passedTime=5.135; remTime=66.755;
MLUPs=5.12021
[LatticeStatistics] step=5000; t=8.3167e+10; uMax=0.000106256; avEnergy=8.16662e-
10; avRho=1
[LatticeStatistics] step=5000; t=8.3167e+10; uMax=0.000106256; avEnergy=8.16662e-
10; avRho=0.709499
[getResults] ----->>>>> Contact angle: 93.1843 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.655271
[Timer] step=6000; percent=8.57143; passedTime=5.887; remTime=62.7947;
MLUPs=5.15426
[LatticeStatistics] step=6000; t=9.98004e+10; uMax=9.80639e-05; avEnergy=7.24968e-
10; avRho=1
[LatticeStatistics] step=6000; t=9.98004e+10; uMax=9.80639e-05; avEnergy=7.24968e-
10; avRho=0.709499
[getResults] ----->>>>> Contact angle: 93.819 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.634676
[Timer] step=7000; percent=10; passedTime=6.825; remTime=61.425; MLUPs=4.1322
[LatticeStatistics] step=7000; t=1.16434e+11; uMax=9.0582e-05; avEnergy=6.35505e-
10; avRho=1
[LatticeStatistics] step=7000; t=1.16434e+11; uMax=9.0582e-05; avEnergy=6.35505e-
10; avRho=0.709499
[getResults] ----->>>>> Contact angle: 94.4338 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.614772
[Timer] step=8000; percent=11.4286; passedTime=7.569; remTime=58.6598;
MLUPs=5.20268
[LatticeStatistics] step=8000; t=1.33067e+11; uMax=8.37055e-05; avEnergy=5.52735e-
10; avRho=1
[LatticeStatistics] step=8000; t=1.33067e+11; uMax=8.37055e-05; avEnergy=5.52735e-
10; avRho=0.709499
[getResults] ----->>>>> Contact angle: 95.019 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.585227
[Timer] step=9000; percent=12.8571; passedTime=8.31; remTime=56.3233;
MLUPs=5.22372
[LatticeStatistics] step=9000; t=1.49701e+11; uMax=7.7349e-05; avEnergy=4.78139e-
10; avRho=1
[LatticeStatistics] step=9000; t=1.49701e+11; uMax=7.7349e-05; avEnergy=4.78139e-
10; avRho=0.709499
[getResults] ----->>>>> Contact angle: 95.5568 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.537832
[Timer] step=10000; percent=14.2857; passedTime=9.065; remTime=54.39;
MLUPs=5.12698
[LatticeStatistics] step=10000; t=1.66334e+11; uMax=7.14523e-05;
avEnergy=4.11917e-10; avRho=1
[LatticeStatistics] step=10000; t=1.66334e+11; uMax=7.14523e-05;
avEnergy=4.11917e-10; avRho=0.709499
[getResults] ----->>>>> Contact angle: 96.0394 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.482621
[Timer] step=11000; percent=15.7143; passedTime=9.806; remTime=52.5958;
MLUPs=5.23784
[LatticeStatistics] step=11000; t=1.82967e+11; uMax=6.59763e-05;
avEnergy=3.53741e-10; avRho=1
[LatticeStatistics] step=11000; t=1.82967e+11; uMax=6.59763e-05;
avEnergy=3.53741e-10; avRho=0.709499
```

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[getResults] ----->>>>> Contact angle: 96.4749 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.435462
[Timer] step=12000; percent=17.1429; passedTime=10.573; remTime=51.1028;
MLUPs=5.04688
[LatticeStatistics] step=12000; t=1.99601e+11; uMax=6.08952e-05;
avEnergy=3.03042e-10; avRho=1
[LatticeStatistics] step=12000; t=1.99601e+11; uMax=6.08952e-05;
avEnergy=3.03042e-10; avRho=0.709499
[getResults] ----->>>>> Contact angle: 96.8695 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.394642
[Timer] step=13000; percent=18.5714; passedTime=11.323; remTime=49.647;
MLUPs=5.168
[LatticeStatistics] step=13000; t=2.16234e+11; uMax=5.61893e-05;
avEnergy=2.59154e-10; avRho=1
[LatticeStatistics] step=13000; t=2.16234e+11; uMax=5.61893e-05;
avEnergy=2.59154e-10; avRho=0.709499
[getResults] ----->>>>> Contact angle: 97.2286 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.35907
[Timer] step=14000; percent=20; passedTime=12.096; remTime=48.384; MLUPs=5.01423
[LatticeStatistics] step=14000; t=2.32868e+11; uMax=5.1841e-05; avEnergy=2.21368e-
10; avRho=1
[LatticeStatistics] step=14000; t=2.32868e+11; uMax=5.1841e-05; avEnergy=2.21368e-
10; avRho=0.709499
[getResults] ----->>>>> Contact angle: 97.5565 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.327872
[Timer] step=15000; percent=21.4286; passedTime=12.846; remTime=47.102;
MLUPs=5.168
[LatticeStatistics] step=15000; t=2.49501e+11; uMax=4.78319e-05;
avEnergy=1.88978e-10; avRho=1
[LatticeStatistics] step=15000; t=2.49501e+11; uMax=4.78319e-05;
avEnergy=1.88978e-10; avRho=0.7095
[getResults] ----->>>>> Contact angle: 97.8568 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.300336
[Timer] step=16000; percent=22.8571; passedTime=13.676; remTime=46.1565;
MLUPs=4.66426
[LatticeStatistics] step=16000; t=2.66134e+11; uMax=4.41423e-05;
avEnergy=1.61305e-10; avRho=1
[LatticeStatistics] step=16000; t=2.66134e+11; uMax=4.41423e-05;
avEnergy=1.61305e-10; avRho=0.7095
[getResults] ----->>>>> Contact angle: 98.1327 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.275886
[Timer] step=17000; percent=24.2857; passedTime=14.446; remTime=45.0375;
MLUPs=5.03377
[LatticeStatistics] step=17000; t=2.82768e+11; uMax=4.07514e-05;
avEnergy=1.37718e-10; avRho=1
[LatticeStatistics] step=17000; t=2.82768e+11; uMax=4.07514e-05;
avEnergy=1.37718e-10; avRho=0.7095
[getResults] ----->>>>> Contact angle: 98.3868 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.254051
[Timer] step=18000; percent=25.7143; passedTime=15.217; remTime=43.9602;
MLUPs=5.02724
[LatticeStatistics] step=18000; t=2.99401e+11; uMax=3.76471e-05;
avEnergy=1.17643e-10; avRho=1
[LatticeStatistics] step=18000; t=2.99401e+11; uMax=3.76471e-05;
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avEnergy=1.17643e-10; avRho=0.7095
[getResults] ----->>>>> Contact angle: 98.6212 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.234443
[Timer] step=19000; percent=27.1429; passedTime=15.987; remTime=42.9125;
MLUPs=5.04031
[LatticeStatistics] step=19000; t=3.16035e+11; uMax=3.47941e-05;
avEnergy=1.00569e-10; avRho=1
[LatticeStatistics] step=19000; t=3.16035e+11; uMax=3.47941e-05;
avEnergy=1.00569e-10; avRho=0.7095
[getResults] ----->>>>> Contact angle: 98.8379 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.216745
[Timer] step=20000; percent=28.5714; passedTime=16.763; remTime=41.9075;
MLUPs=4.98842
[LatticeStatistics] step=20000; t=3.32668e+11; uMax=3.2172e-05; avEnergy=8.60493e-
11; avRho=1
[LatticeStatistics] step=20000; t=3.32668e+11; uMax=3.2172e-05; avEnergy=8.60493e-
11; avRho=0.7095
[getResults] ----->>>>> Contact angle: 99.0386 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.200695
[Timer] step=21000; percent=30; passedTime=17.706; remTime=41.314; MLUPs=4.10593
[LatticeStatistics] step=21000; t=3.49301e+11; uMax=2.97619e-05;
avEnergy=7.36973e-11; avRho=1
[LatticeStatistics] step=21000; t=3.49301e+11; uMax=2.97619e-05;
avEnergy=7.36973e-11; avRho=0.7095
[getResults] ----->>>>> Contact angle: 99.2247 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.186079
[Timer] step=22000; percent=31.4286; passedTime=18.64; remTime=40.6691;
MLUPs=4.14989
[LatticeStatistics] step=22000; t=3.65935e+11; uMax=2.75456e-05;
avEnergy=6.31827e-11; avRho=1
[LatticeStatistics] step=22000; t=3.65935e+11; uMax=2.75456e-05;
avEnergy=6.31827e-11; avRho=0.7095
[getResults] ----->>>>> Contact angle: 99.3974 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.172717
[Timer] step=23000; percent=32.8571; passedTime=19.405; remTime=39.6537;
MLUPs=5.06005
[LatticeStatistics] step=23000; t=3.82568e+11; uMax=2.55065e-05;
avEnergy=5.42243e-11; avRho=1
[LatticeStatistics] step=23000; t=3.82568e+11; uMax=2.55065e-05;
avEnergy=5.42243e-11; avRho=0.7095
[getResults] ----->>>>> Contact angle: 99.5579 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.16046
[Timer] step=24000; percent=34.2857; passedTime=20.24; remTime=38.7933;
MLUPs=4.64192
[LatticeStatistics] step=24000; t=3.99202e+11; uMax=2.36294e-05;
avEnergy=4.65841e-11; avRho=1
[LatticeStatistics] step=24000; t=3.99202e+11; uMax=2.36294e-05;
avEnergy=4.65841e-11; avRho=0.7095
[getResults] ----->>>>> Contact angle: 99.7071 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.149184
[Timer] step=25000; percent=35.7143; passedTime=20.987; remTime=37.7766;
MLUPs=5.18876
[LatticeStatistics] step=25000; t=4.15835e+11; uMax=2.19005e-05;
avEnergy=4.00613e-11; avRho=1
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[LatticeStatistics] step=25000; t=4.15835e+11; uMax=2.19005e-05;
avEnergy=4.00613e-11; avRho=0.7095
[getResults] ----->>>>> Contact angle: 99.8459 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.138786
[Timer] step=26000; percent=37.1429; passedTime=21.729; remTime=36.7722;
MLUPs=5.22372
[LatticeStatistics] step=26000; t=4.32468e+11; uMax=2.0307e-05; avEnergy=3.44863e-
11; avRho=1
[LatticeStatistics] step=26000; t=4.32468e+11; uMax=2.0307e-05; avEnergy=3.44863e-
11; avRho=0.7095
[getResults] ----->>>>> Contact angle: 99.975 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.129177
[Timer] step=27000; percent=38.5714; passedTime=22.477; remTime=35.7967;
MLUPs=5.18182
[LatticeStatistics] step=27000; t=4.49102e+11; uMax=1.88376e-05;
avEnergy=2.97162e-11; avRho=1
[LatticeStatistics] step=27000; t=4.49102e+11; uMax=1.88376e-05;
avEnergy=2.97162e-11; avRho=0.7095
[getResults] ----->>>>> Contact angle: 100.095 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.120281
[Timer] step=28000; percent=40; passedTime=23.225; remTime=34.8375; MLUPs=5.18182
[LatticeStatistics] step=28000; t=4.65735e+11; uMax=1.74819e-05;
avEnergy=2.56305e-11; avRho=1
[LatticeStatistics] step=28000; t=4.65735e+11; uMax=1.74819e-05;
avEnergy=2.56305e-11; avRho=0.7095
[getResults] ----->>>>> Contact angle: 100.207 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.112035
[Timer] step=29000; percent=41.4286; passedTime=23.978; remTime=33.8999;
MLUPs=5.15426
[LatticeStatistics] step=29000; t=4.82369e+11; uMax=1.62305e-05;
avEnergy=2.21276e-11; avRho=1
[LatticeStatistics] step=29000; t=4.82369e+11; uMax=1.62305e-05;
avEnergy=2.21276e-11; avRho=0.7095
[getResults] ----->>>>> Contact angle: 100.312 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.104433
[Timer] step=30000; percent=42.8571; passedTime=24.837; remTime=33.116;
MLUPs=4.50698
[LatticeStatistics] step=30000; t=4.99002e+11; uMax=1.5075e-05; avEnergy=1.91214e-
11; avRho=1
[LatticeStatistics] step=30000; t=4.99002e+11; uMax=1.5075e-05; avEnergy=1.91214e-
11; avRho=0.7095
[getResults] ----->>>>> Contact angle: 100.409 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.0970788
[Timer] step=31000; percent=44.2857; passedTime=25.613; remTime=32.2228;
MLUPs=4.99485
[LatticeStatistics] step=31000; t=5.15635e+11; uMax=1.40076e-05;
avEnergy=1.65392e-11; avRho=1
[LatticeStatistics] step=31000; t=5.15635e+11; uMax=1.40076e-05;
avEnergy=1.65392e-11; avRho=0.7095
[getResults] ----->>>>> Contact angle: 100.499 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.0902512
[Timer] step=32000; percent=45.7143; passedTime=26.364; remTime=31.3072;
MLUPs=5.15426
[LatticeStatistics] step=32000; t=5.32269e+11; uMax=1.30212e-05;
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avEnergy=1.43192e-11; avRho=1
[LatticeStatistics] step=32000; t=5.32269e+11; uMax=1.30212e-05;
avEnergy=1.43192e-11; avRho=0.709501
[getResults] ----->>>>> Contact angle: 100.583 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.0839243
[Timer] step=33000; percent=47.1429; passedTime=27.133; remTime=30.4218;
MLUPs=5.04031
[LatticeStatistics] step=33000; t=5.48902e+11; uMax=1.21104e-05; avEnergy=1.2409e-
11; avRho=1
[LatticeStatistics] step=33000; t=5.48902e+11; uMax=1.21104e-05; avEnergy=1.2409e-
11; avRho=0.709501
[getResults] ----->>>>> Contact angle: 100.661 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.078059
[Timer] step=34000; percent=48.5714; passedTime=27.887; remTime=29.5274;
MLUPs=5.14058
[LatticeStatistics] step=34000; t=5.65536e+11; uMax=1.12698e-05;
avEnergy=1.07641e-11; avRho=1
[LatticeStatistics] step=34000; t=5.65536e+11; uMax=1.12698e-05;
avEnergy=1.07641e-11; avRho=0.709501
[getResults] ----->>>>> Contact angle: 100.734 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.0726202
[Timer] step=35000; percent=50; passedTime=28.644; remTime=28.644; MLUPs=5.11346
[LatticeStatistics] step=35000; t=5.82169e+11; uMax=1.04925e-05;
avEnergy=9.34643e-12; avRho=1
[LatticeStatistics] step=35000; t=5.82169e+11; uMax=1.04925e-05;
avEnergy=9.34643e-12; avRho=0.709501
[getResults] ----->>>>> Contact angle: 100.801 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.0675756
[Timer] step=36000; percent=51.4286; passedTime=29.437; remTime=27.8016;
MLUPs=4.88161
[LatticeStatistics] step=36000; t=5.98802e+11; uMax=9.77346e-06;
avEnergy=8.12375e-12; avRho=1
[LatticeStatistics] step=36000; t=5.98802e+11; uMax=9.77346e-06;
avEnergy=8.12375e-12; avRho=0.709501
[getResults] ----->>>>> Contact angle: 100.864 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.0628962
[Timer] step=37000; percent=52.8571; passedTime=30.254; remTime=26.9833;
MLUPs=4.74419
[LatticeStatistics] step=37000; t=6.15436e+11; uMax=9.10824e-06;
avEnergy=7.06841e-12; avRho=1
[LatticeStatistics] step=37000; t=6.15436e+11; uMax=9.10824e-06;
avEnergy=7.06841e-12; avRho=0.709501
[getResults] ----->>>>> Contact angle: 100.922 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.0580909
[Timer] step=38000; percent=54.2857; passedTime=31.024; remTime=26.1255;
MLUPs=5.02724
[LatticeStatistics] step=38000; t=6.32069e+11; uMax=8.49266e-06;
avEnergy=6.15681e-12; avRho=1
[LatticeStatistics] step=38000; t=6.32069e+11; uMax=8.49266e-06;
avEnergy=6.15681e-12; avRho=0.709501
[getResults] ----->>>>> Contact angle: 100.976 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.0534643
[Timer] step=39000; percent=55.7143; passedTime=31.764; remTime=25.2483;
MLUPs=5.24493
```

```
[LatticeStatistics] step=39000; t=6.48703e+11; uMax=7.92289e-06;
avEnergy=5.36876e-12; avRho=1
[LatticeStatistics] step=39000; t=6.48703e+11; uMax=7.92289e-06;
avEnergy=5.36876e-12; avRho=0.709501
[getResults] ----->>>>> Contact angle: 101.025 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.0493713
[Timer] step=40000; percent=57.1429; passedTime=32.612; remTime=24.459;
MLUPs=4.56537
[LatticeStatistics] step=40000; t=6.65336e+11; uMax=7.39543e-06;
avEnergy=4.68698e-12; avRho=1
[LatticeStatistics] step=40000; t=6.65336e+11; uMax=7.39543e-06;
avEnergy=4.68698e-12; avRho=0.709501
[getResults] ----->>>>> Contact angle: 101.071 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.0456135
[Timer] step=41000; percent=58.5714; passedTime=33.964; remTime=24.0233;
MLUPs=2.86899
[LatticeStatistics] step=41000; t=6.81969e+11; uMax=6.90703e-06;
avEnergy=4.09667e-12; avRho=1
[LatticeStatistics] step=41000; t=6.81969e+11; uMax=6.90703e-06;
avEnergy=4.09667e-12; avRho=0.709501
[getResults] ----->>>>> Contact angle: 101.113 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.0421616
[Timer] step=42000; percent=60; passedTime=34.717; remTime=23.1447; MLUPs=5.14058
[LatticeStatistics] step=42000; t=6.98603e+11; uMax=6.45471e-06;
avEnergy=3.58514e-12; avRho=1
[LatticeStatistics] step=42000; t=6.98603e+11; uMax=6.45471e-06;
avEnergy=3.58514e-12; avRho=0.709501
[getResults] ----->>>>> Contact angle: 101.152 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.038989
[Timer] step=43000; percent=61.4286; passedTime=35.477; remTime=22.2763; MLUPs=5.1
[LatticeStatistics] step=43000; t=7.15236e+11; uMax=6.03573e-06;
avEnergy=3.14151e-12; avRho=1
[LatticeStatistics] step=43000; t=7.15236e+11; uMax=6.03573e-06;
avEnergy=3.14151e-12; avRho=0.709501
[getResults] ----->>>>> Contact angle: 101.188 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.0360718
[Timer] step=44000; percent=62.8571; passedTime=36.241; remTime=21.4151;
MLUPs=5.0733
[LatticeStatistics] step=44000; t=7.3187e+11; uMax=5.64753e-06; avEnergy=2.75642e-
12; avRho=1
[LatticeStatistics] step=44000; t=7.3187e+11; uMax=5.64753e-06; avEnergy=2.75642e-
12; avRho=0.709501
[getResults] ----->>>>> Contact angle: 101.221 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.0333882
[Timer] step=45000; percent=64.2857; passedTime=37.001; remTime=20.5561; MLUPs=5.1
[LatticeStatistics] step=45000; t=7.48503e+11; uMax=5.28778e-06;
avEnergy=2.42184e-12; avRho=1
[LatticeStatistics] step=45000; t=7.48503e+11; uMax=5.28778e-06;
avEnergy=2.42184e-12; avRho=0.709501
[getResults] ----->>>>> Contact angle: 101.252 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.0309186
[Timer] step=46000; percent=65.7143; passedTime=37.812; remTime=19.728;
MLUPs=4.77928
[LatticeStatistics] step=46000; t=7.65136e+11; uMax=4.95432e-06;
```

```
avEnergy=2.13089e-12; avRho=1
[LatticeStatistics] step=46000; t=7.65136e+11; uMax=4.95432e-06;
avEnergy=2.13089e-12; avRho=0.709501
[getResults] ----->>>>> Contact angle: 101.281 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.028645
[Timer] step=47000; percent=67.1429; passedTime=38.58; remTime=18.8796;
MLUPs=5.04031
[LatticeStatistics] step=47000; t=7.8177e+11; uMax=4.64516e-06; avEnergy=1.87763e-
12; avRho=1
[LatticeStatistics] step=47000; t=7.8177e+11; uMax=4.64516e-06; avEnergy=1.87763e-
12; avRho=0.709501
[getResults] ----->>>>> Contact angle: 101.307 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.0265511
[Timer] step=48000; percent=68.5714; passedTime=39.333; remTime=18.0276;
MLUPs=5.14741
[LatticeStatistics] step=48000; t=7.98403e+11; uMax=4.35844e-06;
avEnergy=1.65695e-12; avRho=1
[LatticeStatistics] step=48000; t=7.98403e+11; uMax=4.35844e-06;
avEnergy=1.65695e-12; avRho=0.709501
[getResults] ----->>>>> Contact angle: 101.332 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.0246222
[Timer] step=49000; percent=70; passedTime=40.109; remTime=17.1896; MLUPs=4.98842
[LatticeStatistics] step=49000; t=8.15037e+11; uMax=4.09248e-06;
avEnergy=1.46446e-12; avRho=1
[LatticeStatistics] step=49000; t=8.15037e+11; uMax=4.09248e-06;
avEnergy=1.46446e-12; avRho=0.709501
[getResults] ----->>>>> Contact angle: 101.355 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.0228445
[Timer] step=50000; percent=71.4286; passedTime=40.863; remTime=16.3452;
MLUPs=5.14058
[LatticeStatistics] step=50000; t=8.3167e+11; uMax=3.84569e-06; avEnergy=1.29639e-
12; avRho=1
[LatticeStatistics] step=50000; t=8.3167e+11; uMax=3.84569e-06; avEnergy=1.29639e-
12; avRho=0.709501
[getResults] ----->>>>> Contact angle: 101.376 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.0212059
[Timer] step=51000; percent=72.8571; passedTime=41.803; remTime=15.5737;
MLUPs=4.1234
[LatticeStatistics] step=51000; t=8.48303e+11; uMax=3.61662e-06;
avEnergy=1.14946e-12; avRho=1
[LatticeStatistics] step=51000; t=8.48303e+11; uMax=3.61662e-06;
avEnergy=1.14946e-12; avRho=0.709501
[getResults] ----->>>>> Contact angle: 101.396 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.0196948
[Timer] step=52000; percent=74.2857; passedTime=42.56; remTime=14.7323;
MLUPs=5.11346
[LatticeStatistics] step=52000; t=8.64937e+11; uMax=3.40394e-06;
avEnergy=1.02088e-12; avRho=1
[LatticeStatistics] step=52000; t=8.64937e+11; uMax=3.40394e-06;
avEnergy=1.02088e-12; avRho=0.709502
[getResults] ----->>>>> Contact angle: 101.414 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.0183011
[Timer] step=53000; percent=75.7143; passedTime=43.348; remTime=13.9041;
MLUPs=4.91878
```

```
[LatticeStatistics] step=53000; t=8.8157e+11; uMax=3.20788e-06; avEnergy=9.08224e-13; avRho=1
[LatticeStatistics] step=53000; t=8.8157e+11; uMax=3.20788e-06; avEnergy=9.08224e-13; avRho=0.709502
[getResults] ----->>>>> Contact angle: 101.431 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.0170152
[Timer] step=54000; percent=77.1429; passedTime=44.105; remTime=13.0681; MLUPs=5.11346
[LatticeStatistics] step=54000; t=8.98204e+11; uMax=3.02617e-06; avEnergy=8.09391e-13; avRho=1
[LatticeStatistics] step=54000; t=8.98204e+11; uMax=3.02617e-06; avEnergy=8.09391e-13; avRho=0.709502
[getResults] ----->>>>> Contact angle: 101.447 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.0158284
[Timer] step=55000; percent=78.5714; passedTime=44.933; remTime=12.2545; MLUPs=4.68116
[LatticeStatistics] step=55000; t=9.14837e+11; uMax=2.85723e-06; avEnergy=7.22579e-13; avRho=1
[LatticeStatistics] step=55000; t=9.14837e+11; uMax=2.85723e-06; avEnergy=7.22579e-13; avRho=0.709502
[getResults] ----->>>>> Contact angle: 101.462 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.0147329
[Timer] step=56000; percent=80; passedTime=45.731; remTime=11.4328; MLUPs=4.85714
[LatticeStatistics] step=56000; t=9.3147e+11; uMax=2.70009e-06; avEnergy=6.46228e-13; avRho=1
[LatticeStatistics] step=56000; t=9.3147e+11; uMax=2.70009e-06; avEnergy=6.46228e-13; avRho=0.709502
[getResults] ----->>>>> Contact angle: 101.475 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.0137212
[Timer] step=57000; percent=81.4286; passedTime=46.491; remTime=10.6032; MLUPs=5.0933
[LatticeStatistics] step=57000; t=9.48104e+11; uMax=2.55387e-06; avEnergy=5.78988e-13; avRho=1
[LatticeStatistics] step=57000; t=9.48104e+11; uMax=2.55387e-06; avEnergy=5.78988e-13; avRho=0.709502
[getResults] ----->>>>> Contact angle: 101.488 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.0127867
[Timer] step=58000; percent=82.8571; passedTime=47.29; remTime=9.78414; MLUPs=4.85106
[LatticeStatistics] step=58000; t=9.64737e+11; uMax=2.41774e-06; avEnergy=5.19691e-13; avRho=1
[LatticeStatistics] step=58000; t=9.64737e+11; uMax=2.41774e-06; avEnergy=5.19691e-13; avRho=0.709502
[getResults] ----->>>>> Contact angle: 101.5 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.0119233
[Timer] step=59000; percent=84.2857; passedTime=48.069; remTime=8.96202; MLUPs=4.96923
[LatticeStatistics] step=59000; t=9.81371e+11; uMax=2.29096e-06; avEnergy=4.67325e-13; avRho=1
[LatticeStatistics] step=59000; t=9.81371e+11; uMax=2.29096e-06; avEnergy=4.67325e-13; avRho=0.709502
[getResults] ----->>>>> Contact angle: 101.511 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.0111253
[Timer] step=60000; percent=85.7143; passedTime=48.812; remTime=8.13533;
```

```
MLUPs=5.21669
[LatticeStatistics] step=60000; t=9.98004e+11; uMax=2.17282e-06;
avEnergy=4.21015e-13; avRho=1
[LatticeStatistics] step=60000; t=9.98004e+11; uMax=2.17282e-06;
avEnergy=4.21015e-13; avRho=0.709502
[getResults] ----->>>>> Contact angle: 101.522 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.0103875
[Timer] step=61000; percent=87.1429; passedTime=49.588; remTime=7.31626;
MLUPs=4.99485
[LatticeStatistics] step=61000; t=1.01464e+12; uMax=2.06267e-06;
avEnergy=3.80001e-13; avRho=1
[LatticeStatistics] step=61000; t=1.01464e+12; uMax=2.06267e-06;
avEnergy=3.80001e-13; avRho=0.709502
[getResults] ----->>>>> Contact angle: 101.531 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.00970526
[Timer] step=62000; percent=88.5714; passedTime=50.361; remTime=6.49819;
MLUPs=5.00775
[LatticeStatistics] step=62000; t=1.03127e+12; uMax=1.95992e-06;
avEnergy=3.43622e-13; avRho=1
[LatticeStatistics] step=62000; t=1.03127e+12; uMax=1.95992e-06;
avEnergy=3.43622e-13; avRho=0.709502
[getResults] ----->>>>> Contact angle: 101.54 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.00907408
[Timer] step=63000; percent=90; passedTime=51.215; remTime=5.69056; MLUPs=4.53864
[LatticeStatistics] step=63000; t=1.0479e+12; uMax=1.86402e-06; avEnergy=3.11307e-
13; avRho=1
[LatticeStatistics] step=63000; t=1.0479e+12; uMax=1.86402e-06; avEnergy=3.11307e-
13; avRho=0.709502
[getResults] ----->>>>> Contact angle: 101.549 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.00849
[Timer] step=64000; percent=91.4286; passedTime=51.987; remTime=4.87378;
MLUPs=5.02073
[LatticeStatistics] step=64000; t=1.06454e+12; uMax=1.77445e-06;
avEnergy=2.82557e-13; avRho=1
[LatticeStatistics] step=64000; t=1.06454e+12; uMax=1.77445e-06;
avEnergy=2.82557e-13; avRho=0.709502
[getResults] ----->>>>> Contact angle: 101.557 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.0079493
[Timer] step=65000; percent=92.8571; passedTime=52.744; remTime=4.05723;
MLUPs=5.12021
[LatticeStatistics] step=65000; t=1.08117e+12; uMax=1.69076e-06;
avEnergy=2.56939e-13; avRho=1
[LatticeStatistics] step=65000; t=1.08117e+12; uMax=1.69076e-06;
avEnergy=2.56939e-13; avRho=0.709502
[getResults] ----->>>>> Contact angle: 101.564 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.0074486
[Timer] step=66000; percent=94.2857; passedTime=53.512; remTime=3.24315;
MLUPs=5.04031
[LatticeStatistics] step=66000; t=1.0978e+12; uMax=1.6125e-06; avEnergy=2.34076e-
13; avRho=1
[LatticeStatistics] step=66000; t=1.0978e+12; uMax=1.6125e-06; avEnergy=2.34076e-
13; avRho=0.709502
[getResults] ----->>>>> Contact angle: 101.571 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.00698476
```

```
[Timer] step=67000; percent=95.7143; passedTime=54.282; remTime=2.43054;
MLUPs=5.02724
[LatticeStatistics] step=67000; t=1.11444e+12; uMax=1.53927e-06;
avEnergy=2.13639e-13; avRho=1
[LatticeStatistics] step=67000; t=1.11444e+12; uMax=1.53927e-06;
avEnergy=2.13639e-13; avRho=0.709502
[getResults] ----->>>>> Contact angle: 101.578 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.00655492
[Timer] step=68000; percent=97.1429; passedTime=55.045; remTime=1.61897;
MLUPs=5.07995
[LatticeStatistics] step=68000; t=1.13107e+12; uMax=1.4707e-06; avEnergy=1.95341e-
13; avRho=1
[LatticeStatistics] step=68000; t=1.13107e+12; uMax=1.4707e-06; avEnergy=1.95341e-
13; avRho=0.709502
[getResults] ----->>>>> Contact angle: 101.584 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.00615643
[Timer] step=69000; percent=98.5714; passedTime=55.805; remTime=0.808768;
MLUPs=5.1
[LatticeStatistics] step=69000; t=1.1477e+12; uMax=1.40645e-06; avEnergy=1.78932e-
13; avRho=1
[LatticeStatistics] step=69000; t=1.1477e+12; uMax=1.40645e-06; avEnergy=1.78932e-
13; avRho=0.709502
[getResults] ----->>>>> Contact angle: 101.59 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.00578685
[Timer] step=70000; percent=100; passedTime=56.543; remTime=0; MLUPs=5.25203
[LatticeStatistics] step=70000; t=1.16434e+12; uMax=1.34621e-06;
avEnergy=1.64192e-13; avRho=1
[LatticeStatistics] step=70000; t=1.16434e+12; uMax=1.34621e-06;
avEnergy=1.64192e-13; avRho=0.709502
[getResults] ----->>>>> Contact angle: 101.595 ; Analytical contact angle: 100.001
[getResults] ----->>>>> Difference to previous: 0.00544394
[Timer]
[Timer] ----------------Summary:Timer----------------
[Timer] measured time (rt) : 56.801s
[Timer] measured time (cpu): 1218.501s
[Timer] average MLUPs :       4.777
[Timer] average MLUPps:       0.017
[Timer] ---------------------------------------------
```

模型验证且运行成功，测试通过。

3. 性能测试

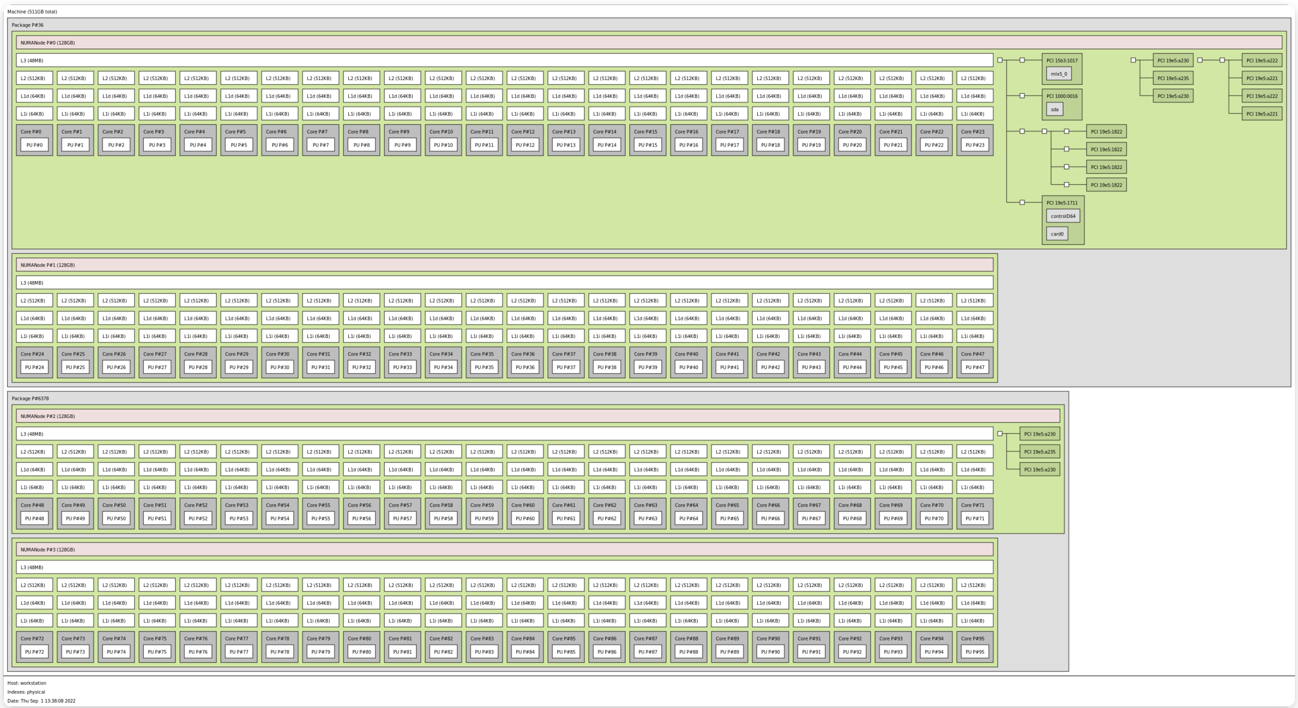
3.1 测试平台对比

具体参数：

	鲲鹏920集群	**Intel x86集群**
服务器型号	TaiShan 2280 V2	XH321 V5

	鲲鹏920集群	Intel x86集群
CPU	2 * Kunpeng 920	2 * Intel(R) Xeon(R) Gold 6248 CPU @ 2.50GHz
内存	488G	186G
Infiniband	Mellanox Technologies MT27800 Family [ConnectX-5]	Mellanox Technologies MT27700 Family [ConnectX-4]
总节点数（不包括控制节点）	3	4
系统	openEuler-21.03	CentOS-7
Kernel	4.18.0-147.el8.aarch64	4.18.0-26-generic

系统拓扑图比较：



鲲鹏920集群

Intel x86集群

3.2 测试软件环境对比

	鲲鹏920集群	Intel x86集群
gcc	gcc version 9.3.1 (GCC)	gcc version 7.5.0 (binhub)
compiler	Bisheng Compiler 1.3.3.b023 clang version 10.0.1	icpc (ICC) 2021.5.0 20211109
mpi	Hyper MPI v1.0.1	Intel(R) MPI Library for Linux* OS, Version 2021.5 Build 20211102
OpenBlas	tsv110p-0.3.21	未使用
KML	1.2.0	未使用
OpenLB	1.4r0	1.4r0

3.3 测试系统性能对比

3.3.1 内存带宽测试

使用内存带宽评测程序Stream进行测试。

内存带宽是处理器可以从内存读取数据或将数据存储到内存的速率

名称	计算模式	bytes/iter	flops/iter
Copy	a(i) = b(i)	16	0
Scale	a(i) = p * b(i)	16	1
Add	a(i) = b(i)+c(i)	24	1
Triad	a(i)= b(i)+p*c(i)	24	2

- Copy： 简单读取写入操作，需要访存两次，是最简单的访存模式。
- Scale： 读取并做乘法操作，共有三次访存。
- Add： 读取加法操作，需要访存三次。
- Triad： 读取内存中的两个数，并做乘加混合运算的操作。

Stream测试数据数组大小（**DSTREAM_ARRAY_SIZE**，数组元素为8字节大小）计算公式设置为:

$$L3 \times 1024 \times 1024 \times 4.1 \times CPU\text{路数}/8$$

$L3$变量为CPU的L3缓存大小，以MB单位计算

鲲鹏920集群L3 cache大小为192M，得出测试数据数组大小为:

$$DSTREAM\_ARRAY\_SIZE = \frac{192 * 1024 * 1024 * 4.1 * 2}{8} = 206359756$$

Intel x86集群L3 cache大小为28160K，得出测试数据数组大小为:

$$DSTREAM\_ARRAY\_SIZE = \frac{28160 * 1024 * 4.1 * 2}{8} = 29556736$$

由此鲲鹏920集群内存带宽程序编译和测试结果如下:

```
[xiehz20@n1 stream]$ clang -Ofast -fopenmp -march=armv8-a -mtune=tsv110 -
mcmodel=large -DSTREAM_ARRAY_SIZE=206359756 -DNTIMES=30 stream.c -o arm/stream
/usr/bin/ld: /opt/app/kunpeng/bisheng/bin/../lib/libomp.so: .dynsym local symbol
at index 26 (>= sh_info of 1)
[xiehz20@n1 stream]$ cd arm/
[xiehz20@n1 arm]$ ./stream
-------------------------------------------------------------
STREAM version $Revision: 5.10 $
-------------------------------------------------------------
This system uses 8 bytes per array element.
-------------------------------------------------------------
Array size = 206359756 (elements), Offset = 0 (elements)
Memory per array = 1574.4 MiB (= 1.5 GiB).
Total memory required = 4723.2 MiB (= 4.6 GiB).
Each kernel will be executed 30 times.
 The *best* time for each kernel (excluding the first iteration)
 will be used to compute the reported bandwidth.
-------------------------------------------------------------
Number of Threads requested = 96
Number of Threads counted = 96
-------------------------------------------------------------
Your clock granularity/precision appears to be 1 microseconds.
Each test below will take on the order of 38268 microseconds.
   (= 38268 clock ticks)
Increase the size of the arrays if this shows that
you are not getting at least 20 clock ticks per test.
-------------------------------------------------------------
WARNING -- The above is only a rough guideline.
For best results, please be sure you know the
precision of your system timer.
-------------------------------------------------------------
Function    Best Rate MB/s  Avg time     Min time     Max time
Copy:          130370.1     0.033824     0.025326     0.044649
Scale:         100388.3     0.049020     0.032890     0.063459
Add:           109868.0     0.071518     0.045078     0.217662
Triad:         109668.5     0.053110     0.045160     0.075044
-------------------------------------------------------------
Solution Validates: avg error less than 1.000000e-13 on all three arrays
-------------------------------------------------------------
```

由此Intel x86集群内存带宽程序编译和测试结果如下：

```
[xiehz20@n1 stream]$ icc -Ofast -qopenmp -xHost -mcmodel=medium -
DSTREAM_ARRAY_SIZE=29556736 -DNTIMES=30 stream.c -o x86/stream
[xiehz20@n1 stream]$ cd x86/
[xiehz20@n1 x86]$ ./stream
-------------------------------------------------------------
STREAM version $Revision: 5.10 $
-------------------------------------------------------------
This system uses 8 bytes per array element.
```

```
-------------------------------------------------------------
Array size = 29556736 (elements), Offset = 0 (elements)
Memory per array = 225.5 MiB (= 0.2 GiB).
Total memory required = 676.5 MiB (= 0.7 GiB).
Each kernel will be executed 30 times.
 The *best* time for each kernel (excluding the first iteration)
 will be used to compute the reported bandwidth.
-------------------------------------------------------------
Number of Threads requested = 40
Number of Threads counted = 40
-------------------------------------------------------------
Your clock granularity/precision appears to be 1 microseconds.
Each test below will take on the order of 3487 microseconds.
   (= 3487 clock ticks)
Increase the size of the arrays if this shows that
you are not getting at least 20 clock ticks per test.
-------------------------------------------------------------
WARNING -- The above is only a rough guideline.
For best results, please be sure you know the
precision of your system timer.
-------------------------------------------------------------
Function    Best Rate MB/s  Avg time     Min time     Max time
Copy:          127779.4     0.004375     0.003701     0.017825
Scale:         117229.3     0.004689     0.004034     0.016958
Add:           130637.9     0.006610     0.005430     0.018949
Triad:         134707.2     0.005888     0.005266     0.018521
-------------------------------------------------------------
Solution Validates: avg error less than 1.000000e-13 on all three arrays
-------------------------------------------------------------
```

3.3.2 Infiniband网络基准测试

对多节点Infiniband网络通信进行测试：

使用`ib_read_bw`、`ib_write_bw`、`ib_send_bw`三个命令对ib通信的各个方面进行测试：

对鲲鹏920集群进行Infiniband网络通信测试：

```
[xiehz20@n1 ~]$ ib_read_bw -F
[xiehz20@n2 ~]$ ib_read_bw -F n1
---------------------------------------------------------------------------------
-----
                    RDMA_Read BW Test
 Dual-port       : OFF          Device         : mlx5_0
 Number of qps   : 1            Transport type : IB
 Connection type : RC           Using SRQ      : OFF
 TX depth        : 128
 CQ Moderation   : 100
 Mtu             : 4096[B]
 Link type       : IB
 Outstand reads  : 16
```

```
 rdma_cm QPs      : OFF
 Data ex. method : Ethernet
---------------------------------------------------------------------------------------
-----
 #bytes     #iterations    BW peak[MB/sec]    BW average[MB/sec]   MsgRate[Mpps]
 65536      1000             11418.94            11398.46
0.182375
---------------------------------------------------------------------------------------
-----
[xiehz20@n1 ~]$ ib_write_bw -F
[xiehz20@n2 ~]$ ib_write_bw -F n1
---------------------------------------------------------------------------------------
-----
                    RDMA_Write BW Test
 Dual-port       : OFF          Device         : mlx5_0
 Number of qps   : 1            Transport type : IB
 Connection type : RC           Using SRQ      : OFF
 TX depth        : 128
 CQ Moderation   : 100
 Mtu             : 4096[B]
 Link type       : IB
 Max inline data : 0[B]
 rdma_cm QPs     : OFF
 Data ex. method : Ethernet
---------------------------------------------------------------------------------------
-----
 #bytes     #iterations    BW peak[MB/sec]    BW average[MB/sec]   MsgRate[Mpps]
 65536      5000             11509.98            11484.90
0.183758
---------------------------------------------------------------------------------------
-----
[xiehz20@n1 ~]$ ib_send_bw -F
[xiehz20@n2 ~]$ ib_send_bw -F n1
---------------------------------------------------------------------------------------
-----
                    Send BW Test
 Dual-port       : OFF          Device         : mlx5_0
 Number of qps   : 1            Transport type : IB
 Connection type : RC           Using SRQ      : OFF
 TX depth        : 128
 CQ Moderation   : 100
 Mtu             : 4096[B]
 Link type       : IB
 Max inline data : 0[B]
 rdma_cm QPs     : OFF
 Data ex. method : Ethernet
---------------------------------------------------------------------------------------
-----
 #bytes     #iterations    BW peak[MB/sec]    BW average[MB/sec]   MsgRate[Mpps]
 65536      1000             11488.91            11472.76
0.183564
---------------------------------------------------------------------------------------
-----
```

在Intel x86集群进行Infiniband网络通信测试：

```
[xiehz20@n1 ~]$ ib_read_bw -F -d mlx5_1
[xiehz20@n2 ~]$ ib_read_bw -F -d mlx5_1 n1
---------------------------------------------------------------------------------
-----
                    RDMA_Read BW Test
 Dual-port       : OFF          Device         : mlx5_1
 Number of qps   : 1            Transport type : IB
 Connection type : RC           Using SRQ      : OFF
 TX depth        : 128
 CQ Moderation   : 100
 Mtu             : 4096[B]
 Link type       : IB
 Outstand reads  : 16
 rdma_cm QPs     : OFF
 Data ex. method : Ethernet
---------------------------------------------------------------------------------
-----
 #bytes     #iterations    BW peak[MB/sec]    BW average[MB/sec]   MsgRate[Mpps]
 65536      1000             10837.63            10832.09
0.173313
---------------------------------------------------------------------------------
-----
[xiehz20@n1 ~]$ ib_write_bw -F -d mlx5_1
[xiehz20@n2 ~]$ ib_write_bw -F -d mlx5_1 n1
---------------------------------------------------------------------------------
-----
                    RDMA_Write BW Test
 Dual-port       : OFF          Device         : mlx5_1
 Number of qps   : 1            Transport type : IB
 Connection type : RC           Using SRQ      : OFF
 TX depth        : 128
 CQ Moderation   : 100
 Mtu             : 4096[B]
 Link type       : IB
 Max inline data : 0[B]
 rdma_cm QPs     : OFF
 Data ex. method : Ethernet
---------------------------------------------------------------------------------
-----
 #bytes     #iterations    BW peak[MB/sec]    BW average[MB/sec]   MsgRate[Mpps]
 65536      5000             11165.22            11142.22
0.178275
---------------------------------------------------------------------------------
-----
[xiehz20@n1 ~]$ ib_send_bw -F -d mlx5_1
[xiehz20@n2 ~]$ ib_send_bw -F -d mlx5_1 n1
---------------------------------------------------------------------------------
-----
                    Send BW Test
 Dual-port       : OFF          Device         : mlx5_1
```

```
 Number of qps   : 1          Transport type : IB
 Connection type : RC         Using SRQ      : OFF
 TX depth        : 128
 CQ Moderation   : 100
 Mtu             : 4096[B]
 Link type       : IB
 Max inline data : 0[B]
 rdma_cm QPs     : OFF
 Data ex. method : Ethernet
---------------------------------------------------------------------------------
-----
 #bytes     #iterations    BW peak[MB/sec]    BW average[MB/sec]   MsgRate[Mpps]
 65536      1000            11600.28            11599.48
0.185592
---------------------------------------------------------------------------------
-----
```

3.4 基准测试选定

考虑到程序运行时间和覆盖到的测试方向，本次移植以`examples`目录下的三个程序为基准进行分析比较：

- **multiComponent/contactAngle2d/contactAngle2d** In this example a semi-circular droplet of fluid is initialised within a different fluid at a solid boundary. The contact angle is measured as the droplet comes to equilibrium. This is compared with the analytical angle (100 degrees) predicted by the parameters set for the boundary.

  This example demonstrates how to use the wetting solid boundaries for the free-energy model with two fluid components.

- **porousMedia/porousPoiseuille3d/porousPoiseuille3d** This example examines a 3D Poiseuille flow with porous media. Two porous media LB methods can be used here:

  - Spaid and Phelan (doi:10.1063/1.869392), or
  - Guo and Zhao (doi:10.1103/PhysRevE.66.036304)

- **laminar/bstep3d/bstep3d** The implementation of a backward facing step. It is furthermore shown how to use checkpointing to save the state of the simulation regularly.

实际运行中，**contactAngle2d和porousPoiseuille3d**程序分析数据较小，运行时间短。而**bstep3d**程序分析迭代步骤多，运行时间较长。

3.5 性能指标选择

3.5.1 可行指标

OpenLB仿真测试程序中比较重要的仿真参数：

1. `N`问题规模（2维仿真程序总量是N^2，3维的同理），表示格子数。
2. 格子大小`x`（2维仿真程序总大小为x^2）。
3. 计算域，即格子大小`x`与问题规模`N`的乘积。

OpenLB内提供的各个实验测试文件最终输出4个性能指标，这些指标的计算与上述的仿真参数有一定关系：

1. measured time（rt/real time）
2. measured time（cpu）
3. average MLUPs
4. average MLUPps

本次测试以上述4个指标为主对OpenLB的移植性能进行测试。

3.5.2 MLUPs & MLUPps

OpenLB基于的格子玻尔兹曼方法（LBM）是一类广泛应用的介观尺度下的流体数值模拟方法。MLUPs是该方法的一个评价指标。

对 LBM 方法运算表现的评判标准为每秒百万格子（Cell）更新数（Million Lattice UPdates per second），其表达式为

$$MLUPs = \frac{n_l * 10^{-6}}{T}$$

n_l为格子数，T为计算耗时

MLUPps（Million Lattice UPdates per core and second）：每秒每个计算单元（core）百万格子更新数：

$$MLUPps = \frac{MLUPs}{cores}$$

3.5.3 measured time

measured time给的是real time和CPU总时间即进程时间（用户态代码耗费的CPU时间 + 内核态代码运行耗费的CPU时间、内核执行系统调用的CPU时间）

这两者关系是：

> real < CPU 表明进程为计算密集型（CPU bound），利用多核处理器的并行执行优势 real ≈ CPU 表明进程为计算密集型，未并行执行 real > CPU 表明进程为I/O密集型 （I/O bound），多核并行执行优势并不明显

实际测试中OpenLB的real time 远小于 CPU Time，是计算密集型应用。

3.5.4 性能指标分析

MLUPs用于比较OpenLB性能。

MLUPps用于比较可扩展性（多机多核并行运行时，各个计算单元是否能承担合理的计算量）。

measured time（runtime、CPU time）可用于大致评价运行时间，作为性能分析的辅助。

3.6 测试性能分析

3.6.1 测试方法

进入OpenLB项目根目录，修改相关`config.mk`文件修改编译参数，本次测试使用GCC串行编译、Intel MPI并行编译和基于毕晟编译器的Hyper MPI并行编译进行对比比较，测试使用`config.mk`文件参数如下：

```
# GCC串行编译参数
CXX             := g++
CC              := gcc
OPTIM           := -O3 -Wall -march=native -mtune=native
DEBUG           := -g -Wall -DOLB_DEBUG
CXXFLAGS        := $(OPTIM)
CXXFLAGS        += -std=c++14
ARPRG           := ar
LDFLAGS         :=
PARALLEL_MODE   := OFF
MPIFLAGS        :=
OMPFLAGS        := -fopenmp
BUILDTYPE       := generic
FEATURES        :=
```

```
# Intel MPI并行编译
CXX             := mpiicpc
CC              := mpiicc                                       # necessary for
zlib, for Intel use icc
OPTIM           := -O3 -Wall -xHost                    # optional for Intel
compiler
DEBUG           := -g -Wall -DOLB_DEBUG
CXXFLAGS        := $(OPTIM)
CXXFLAGS        += -std=c++14
ARPRG           := xiar                  # mandatory for intel compiler
LDFLAGS         :=
PARALLEL_MODE   := HYBRID
MPIFLAGS        :=
OMPFLAGS        := -qopenmp
BUILDTYPE       := generic
FEATURES        :=
```

```
# Hyper MPI并行编译
## 配置参数说明，需要根据平台、系统自行修改
# MTUNE_PARAM - mtune编译参数，根据机器平台修改为合适的参数
# MARCH_PARAM - march编译参数，根据机器平台修改为合适的参数
# CPU_FEATURE_PARAM - march开启平台拓展指令集特性，根据机器平台修改为合适的参数，如crc
# BISHENG_INCLUDE - 毕昇编译器include头文件目录
# KML_INCLUDE - KML数学库include头文件目录
# OPENBLAS_INCLUDE - OPENBLAS代数库include头文件目录
# BISHENG_LIB - 毕昇编译器lib库文件目录
# KML_LIB - KML数学库lib库文件目录
# OPENBLAS_LIB - OPENBLAS数学库lib库文件目录
# IPM_LIB - IPM MPI程序分析库lib库文件目录，通过插桩方式检测MPI程序性能，按需开启
## ------------------------------------
```

```
CXX             := mpicxx
CC              := mpicc                    # necessary for zlib, for Intel use icc
OPTIM           := -Ofast -ffast-math -finline-functions -ffp-contract=fast -Wall -mtune=MTUNE_PARAM -march=MARCH_PARAM+CPU_FEATURE_PARAM -I BISHENG_INCLUDE -I KML_INCLUDE -I OPENBLAS_INCLUDE
DEBUG           := -g -Wall -DOLB_DEBUG
DEBUGNoWall           := -g -DOLB_DEBUG
CXXFLAGS        := $(OPTIM)
# for debug mode
#CXXFLAGS        += $(DEBUGNoWall)
#CXXFLAGS        := $(DEBUG)

# open pgo optimize
PGOCollect      := -fprofile-instr-generate
PGOOptim    := -fprofile-instr-use=code.profdata

CXXFLAGS        += -std=c++14
ARPRG           := ar
LDFLAGS         := -fuse-ld=lld -flto -L OPENBLAS_LIB -lopenblas -L KML_LIB -lkm -lm -lkfft -L BISHENG_LIB -ljemalloc -Wl,-z,muldefs
# for IPM analysis (static used)
# LDFLAGS  += -LIPM_LIB -lipm
# for pgo optimize
#LDFLAGS  += $(PGOCollect)
#LDFLAGS  += $(PGOOptim)
PARALLEL_MODE   := HYBRID
MPIFLAGS        :=
OMPFLAGS        := -fopenmp
BUILDTYPE       := generic
FEATURES        := OPENBLAS
```

使用`make samples -j`进行编译，并进入examples目录运行相关测试程序，每个程序以相同方式运行三次，结果取平均值。

三种编译方式运行命令如下：

- GCC

```
testFile=$1

# run without parallel
${testFile}
```

- Intel MPI

```
#!/bin/bash

testFile=$1
```

```
export I_MPI_PIN_DOMAIN=omp
export OMP_NUM_THREADS=20

mpirun --print-rank-map -np 8 -ppn 2 --map-by ppr:1:numa:pe=20 -machinefile nodes
${testFile}
```

- Hyper MPI

```
#!/bin/bash

testFile=$1

export OMP_NUM_THREADS=24
export OMP_PROC_BIND=true
export OMP_PLACES=cores

mpirun -machinefile nodes -np 12 -npernode 4 --bind-to numa --mca btl
^vader,tcp,openib --map-by numa  --rank-by numa \
    -x UCX_TLS=sm,ud_x -x UCX_NET_DEVICES=mlx5_0:1 \
    -x UCX_BUILTIN_BCAST_ALGORITHM=3 \
    -x UCX_BUILTIN_ALLREDUCE_ALGORITHM=6 \
    -x UCX_BUILTIN_BARRIER_ALGORITHM=5 \
    -x UCX_BUILTIN_DEGREE_INTRA_FANOUT=3 \
    -x UCX_BUILTIN_DEGREE_INTRA_FANIN=2 \
    -x UCX_BUILTIN_DEGREE_INTER_FANOUT=7 \
    -x UCX_BUILTIN_DEGREE_INTER_FANIN=7 \
    --report-bindings ${testFile}
```

由于Intel x86集群在硬件上的限制，无法测试超过160核并行运行的数据，故数据中并未体现。

3.6.2 GCC基准测试

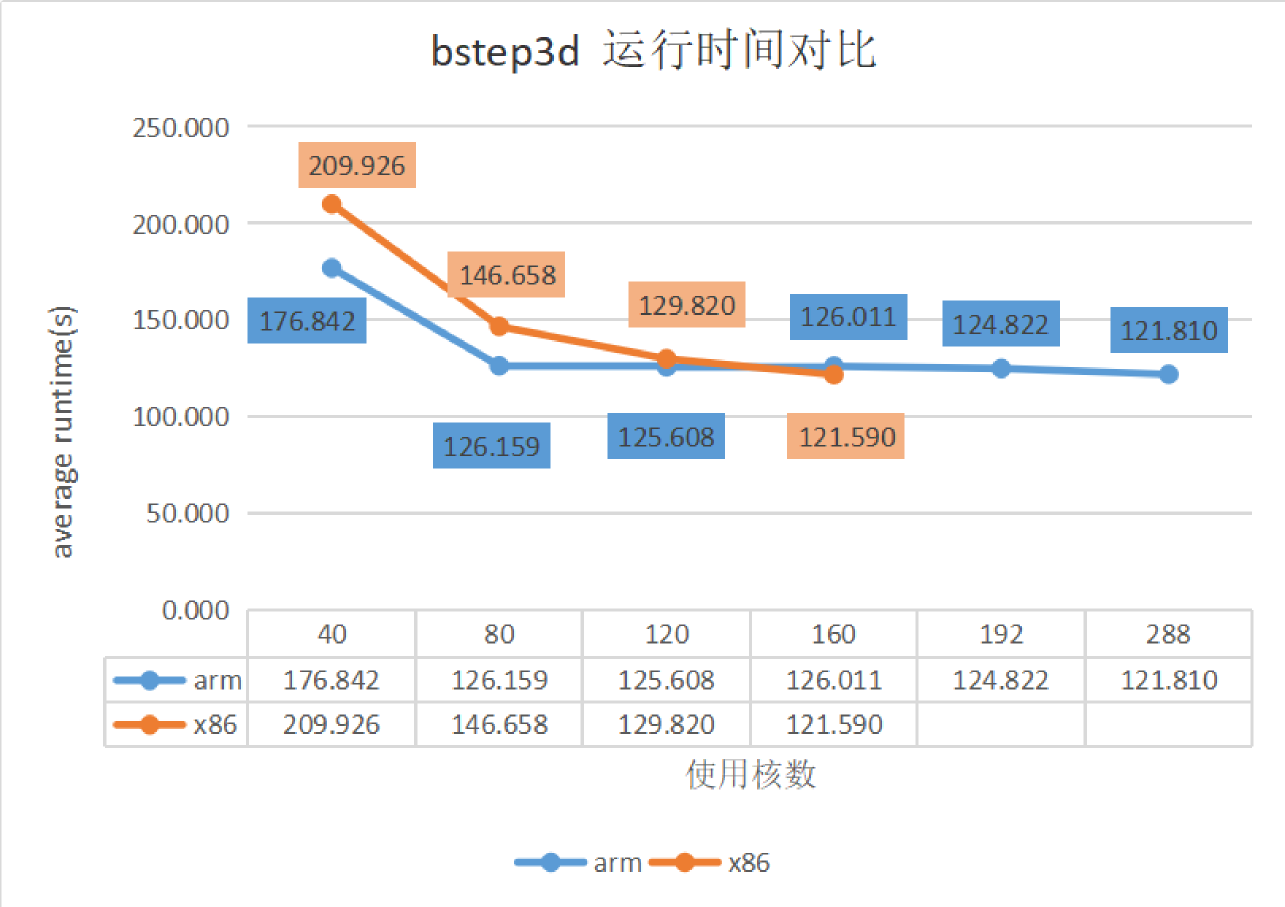
使用默认的GCC编译配置进行测试，并作为基准进行比较，最终测试结果如下：

Program	runtime(s)	CPU time(s)	Average MLUPs	Average MLUPps
bstep3d	960.747	850.372	6.238	6.238
contactAngle2d	171.512	159.074	1.584	1.584
porousPoiseuille3d	11.818	8.712	2.487	2.487

由于是串行运行，只占用一个CPU核，因此CPU time和Average MLUPps和并行运行进行比较时会考虑到核数的差异。

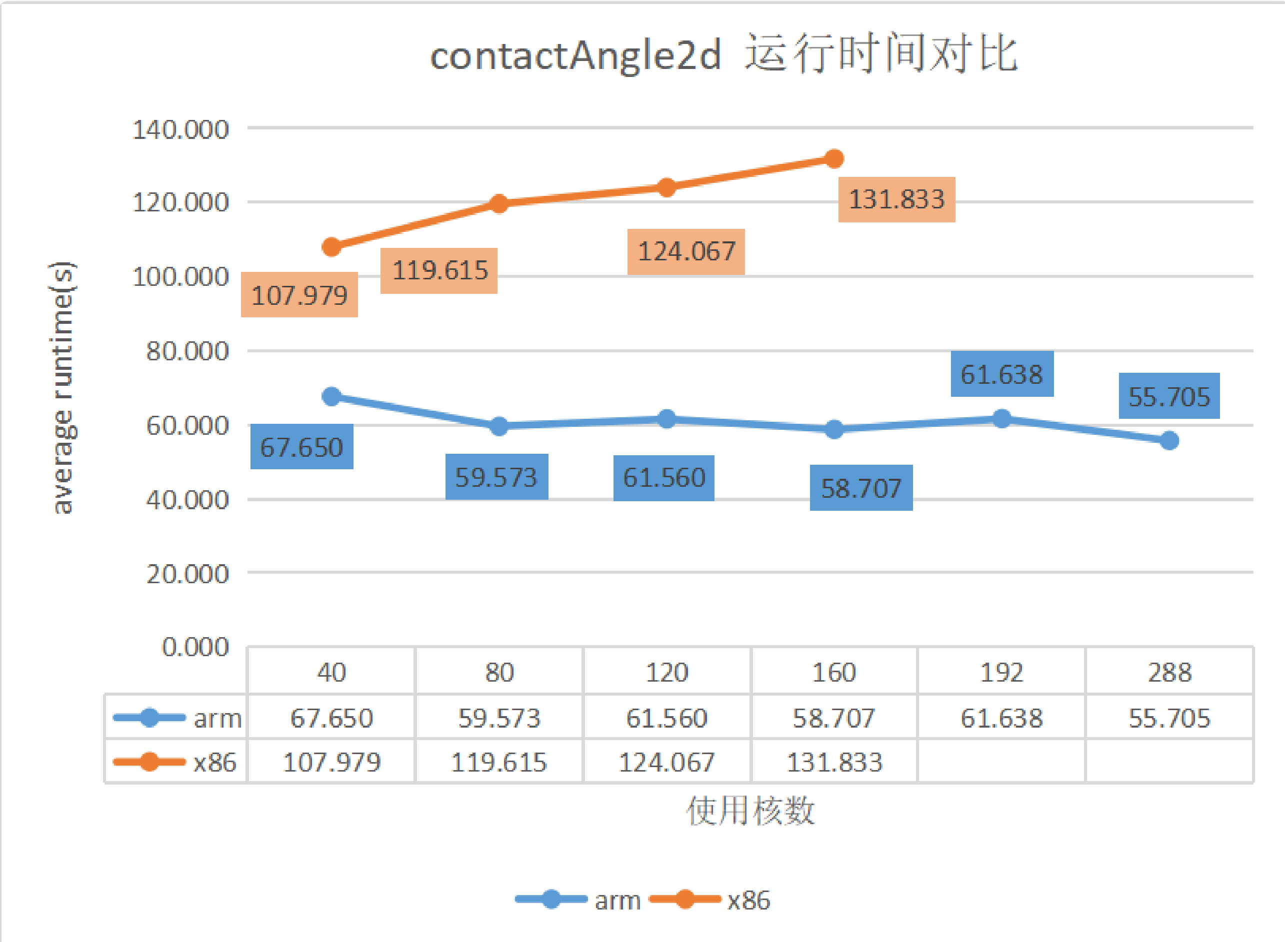
3.6.3 执行时间（runtime）测试

以三个程序分别进行比较，runtime和CPU时间比较越低越好。



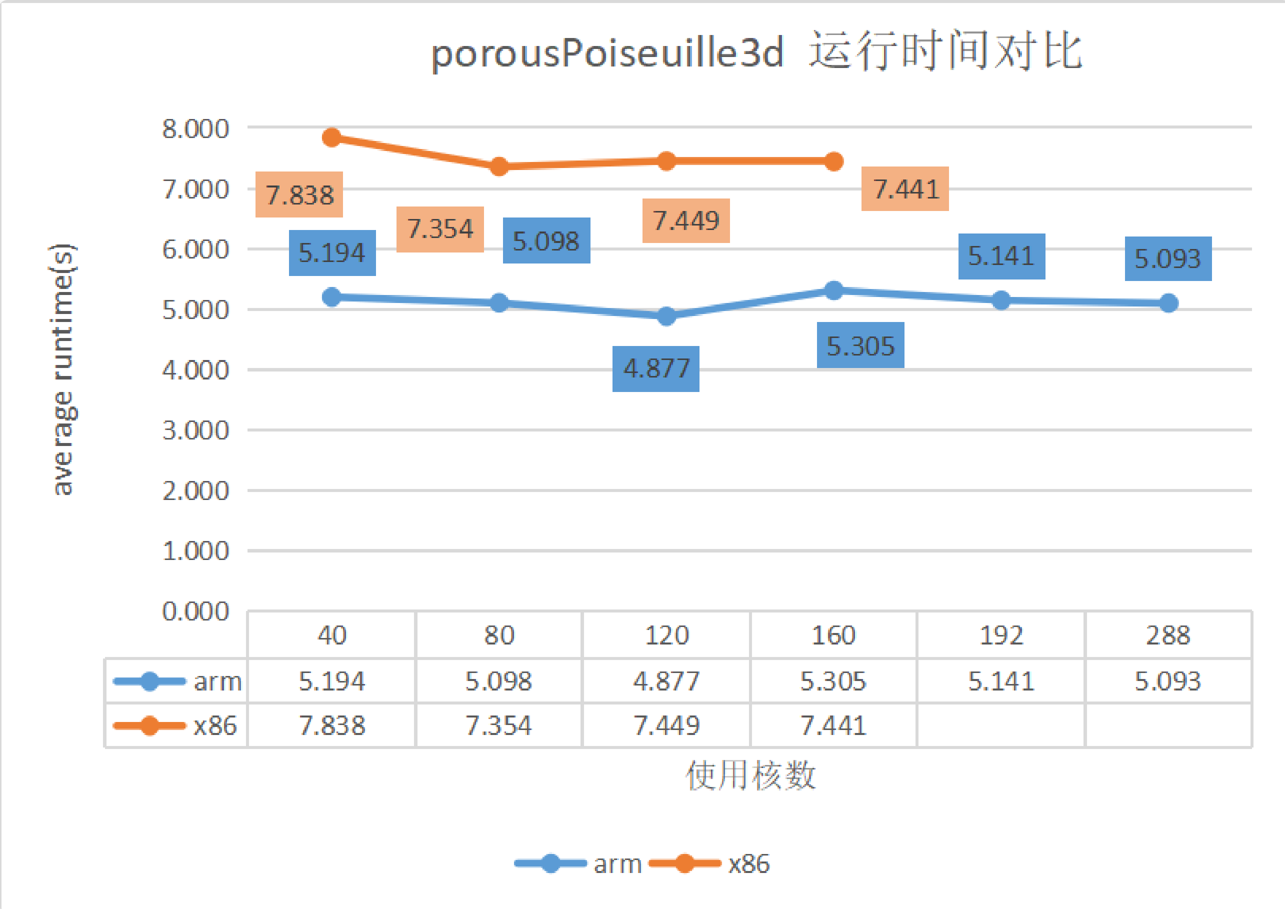
	40	80	120	160	192	288
arm	176.842	126.159	125.608	126.011	124.822	121.810
x86	209.926	146.658	129.820	121.590		

bstesp3d runtime



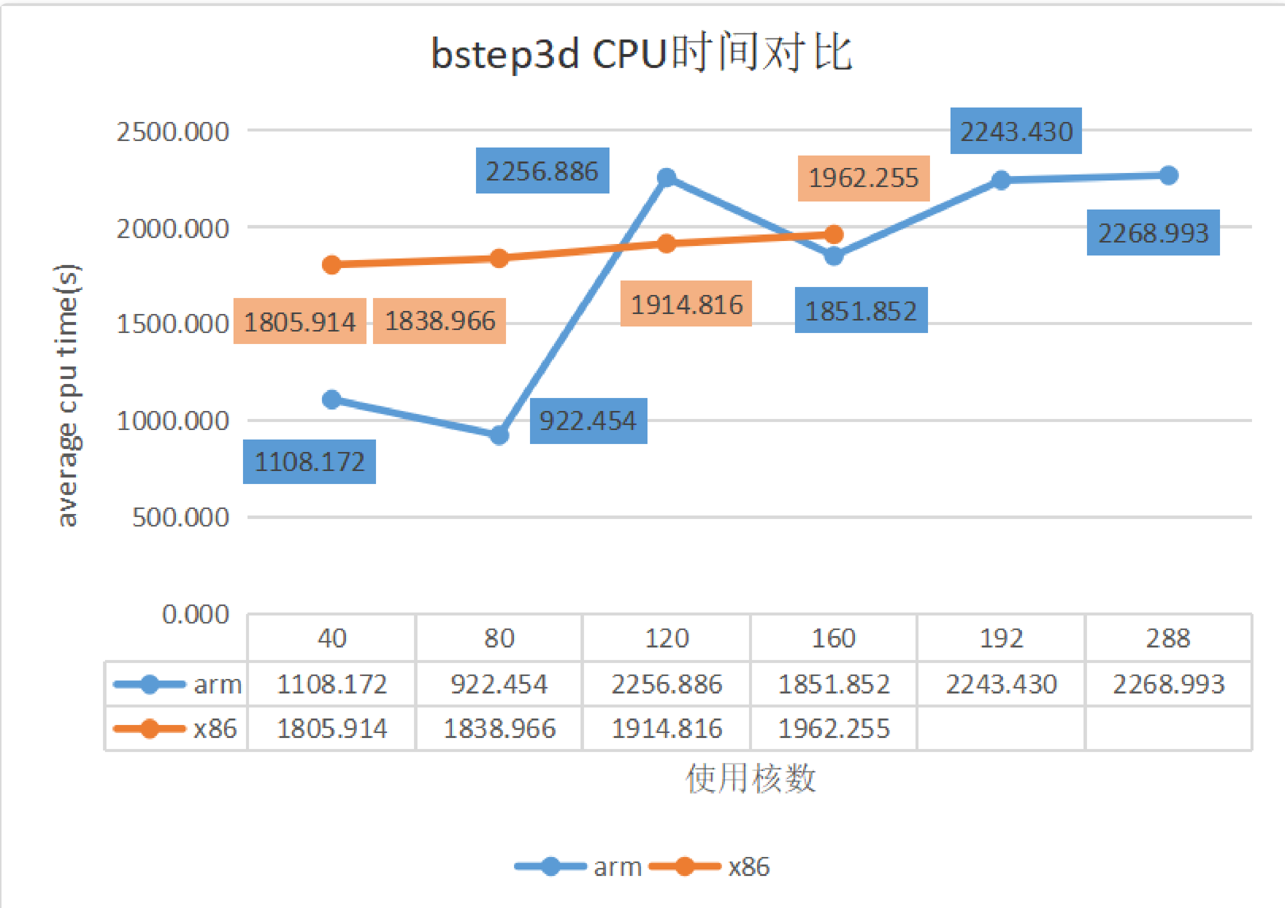
	40	80	120	160	192	288
arm	67.650	59.573	61.560	58.707	61.638	55.705
x86	107.979	119.615	124.067	131.833		

contactAngle2d runtime



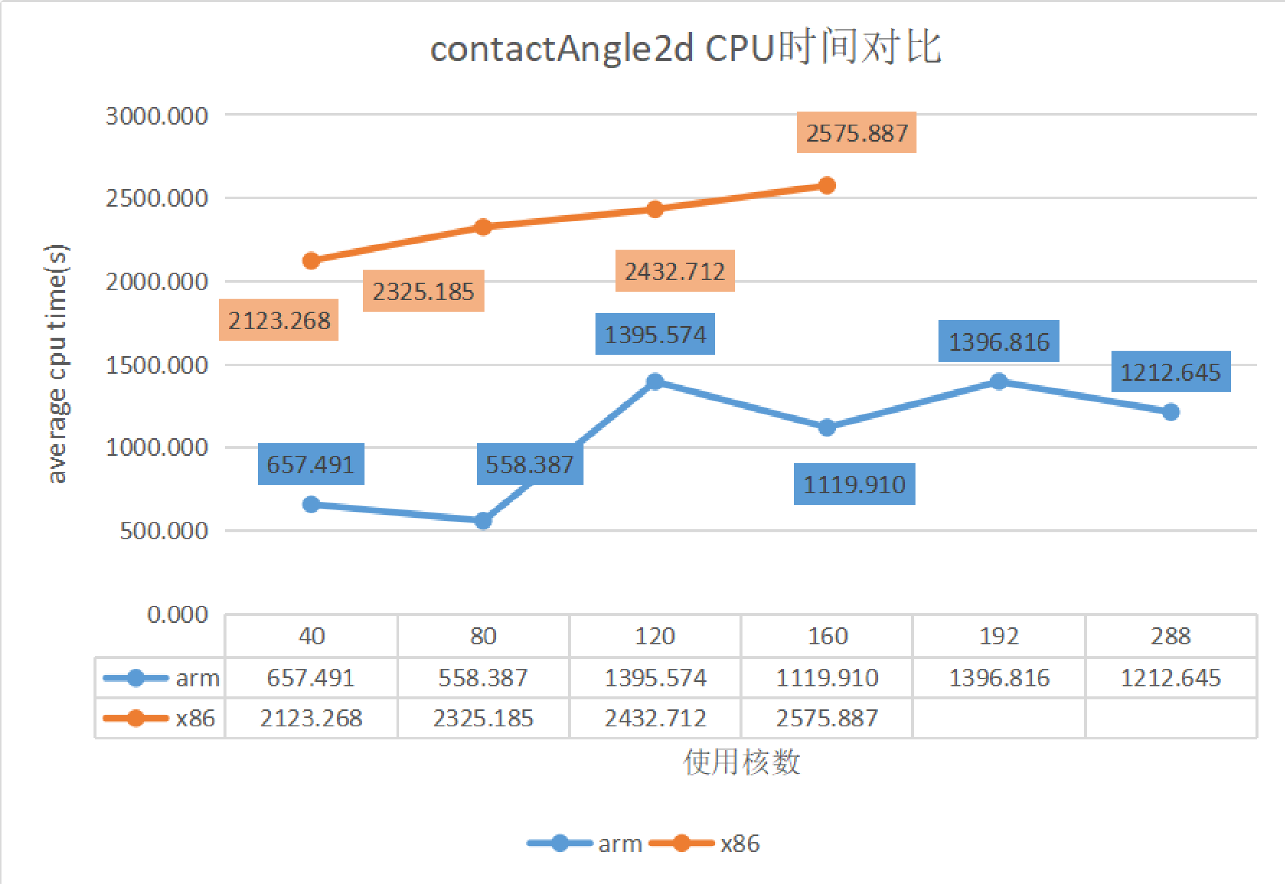
	40	80	120	160	192	288
arm	5.194	5.098	4.877	5.305	5.141	5.093
x86	7.838	7.354	7.449	7.441		

porousPoiseuille3d runtime

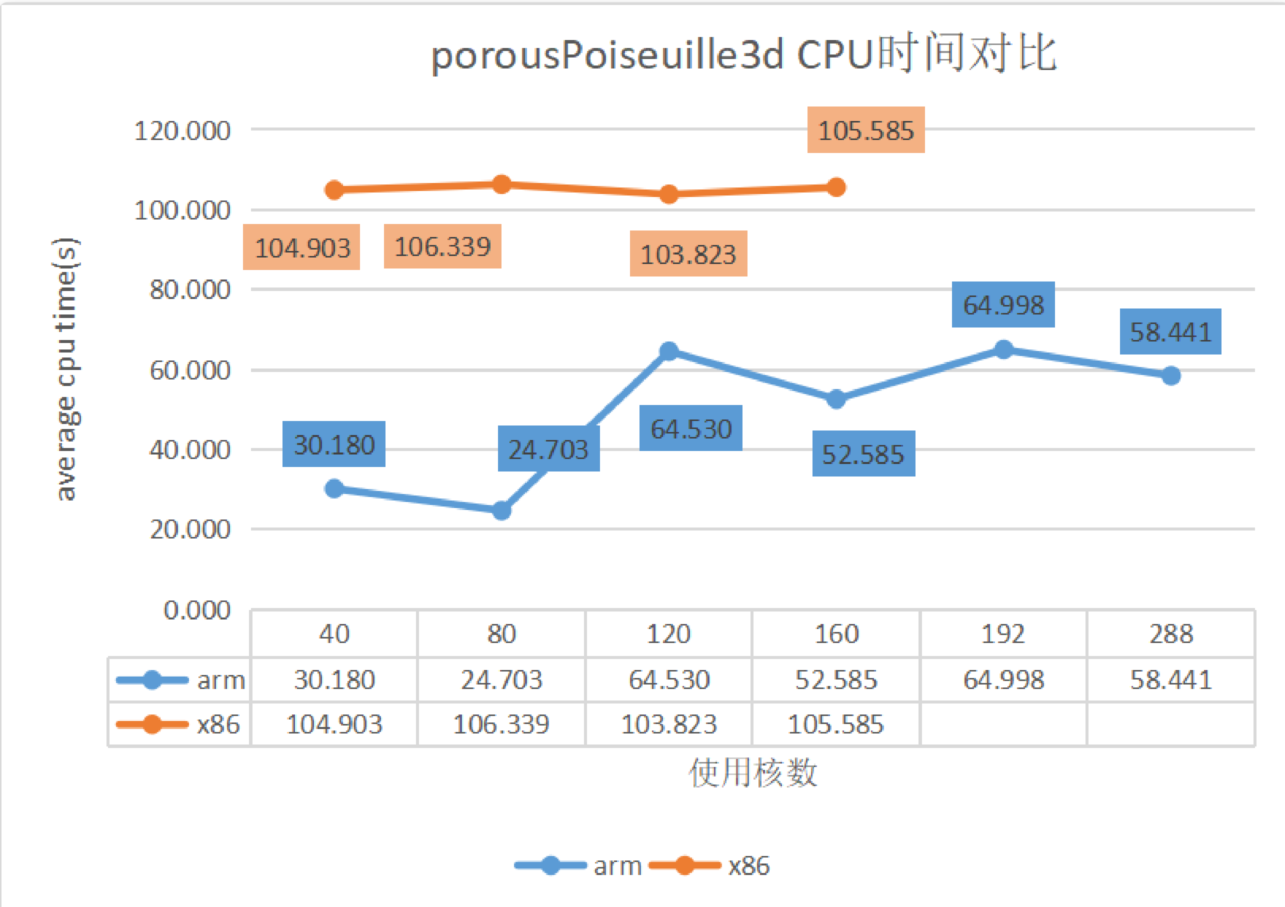


	40	80	120	160	192	288
arm	1108.172	922.454	2256.886	1851.852	2243.430	2268.993
x86	1805.914	1838.966	1914.816	1962.255		

bstesp3d CPU Time



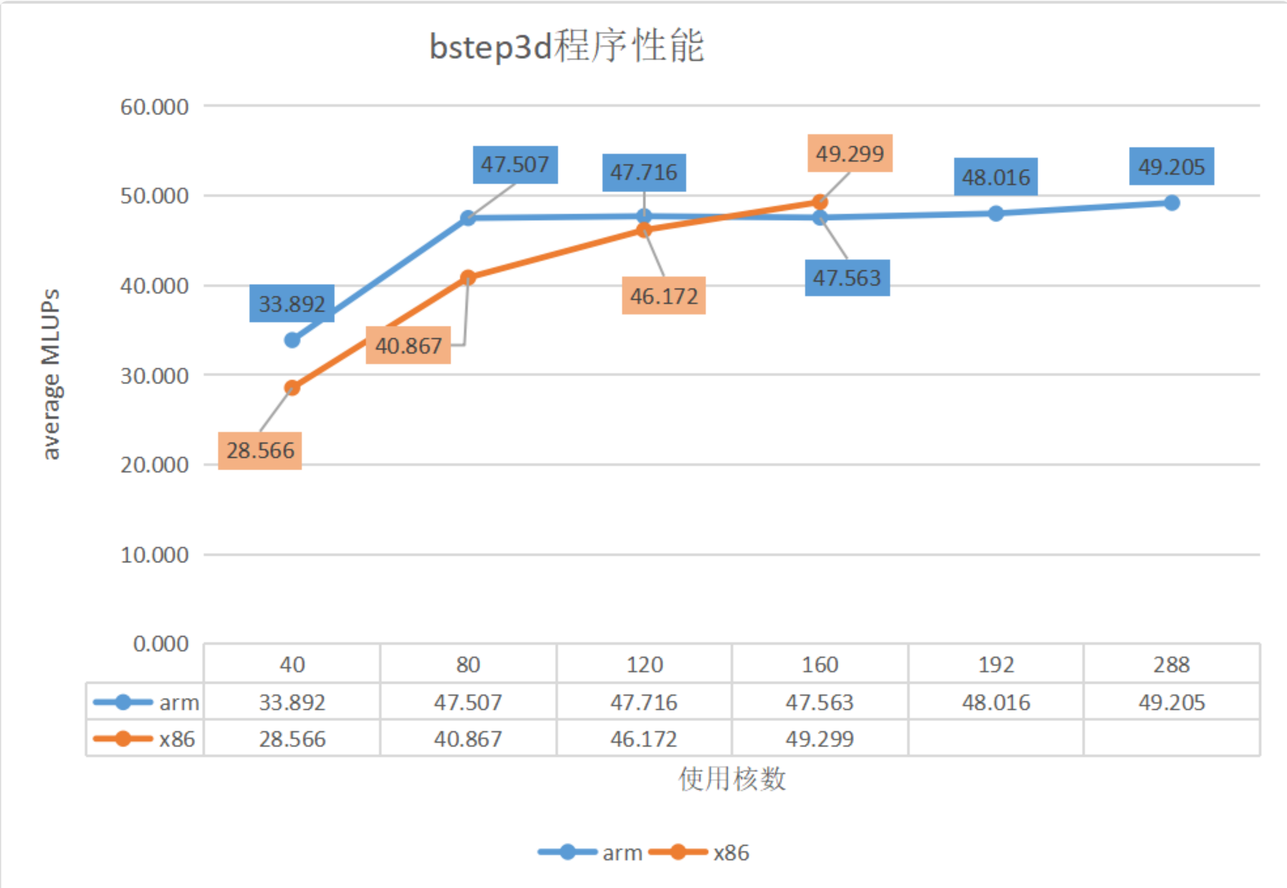
contactAngle2d CPU Time



porousPoiseuille3d CPU Time

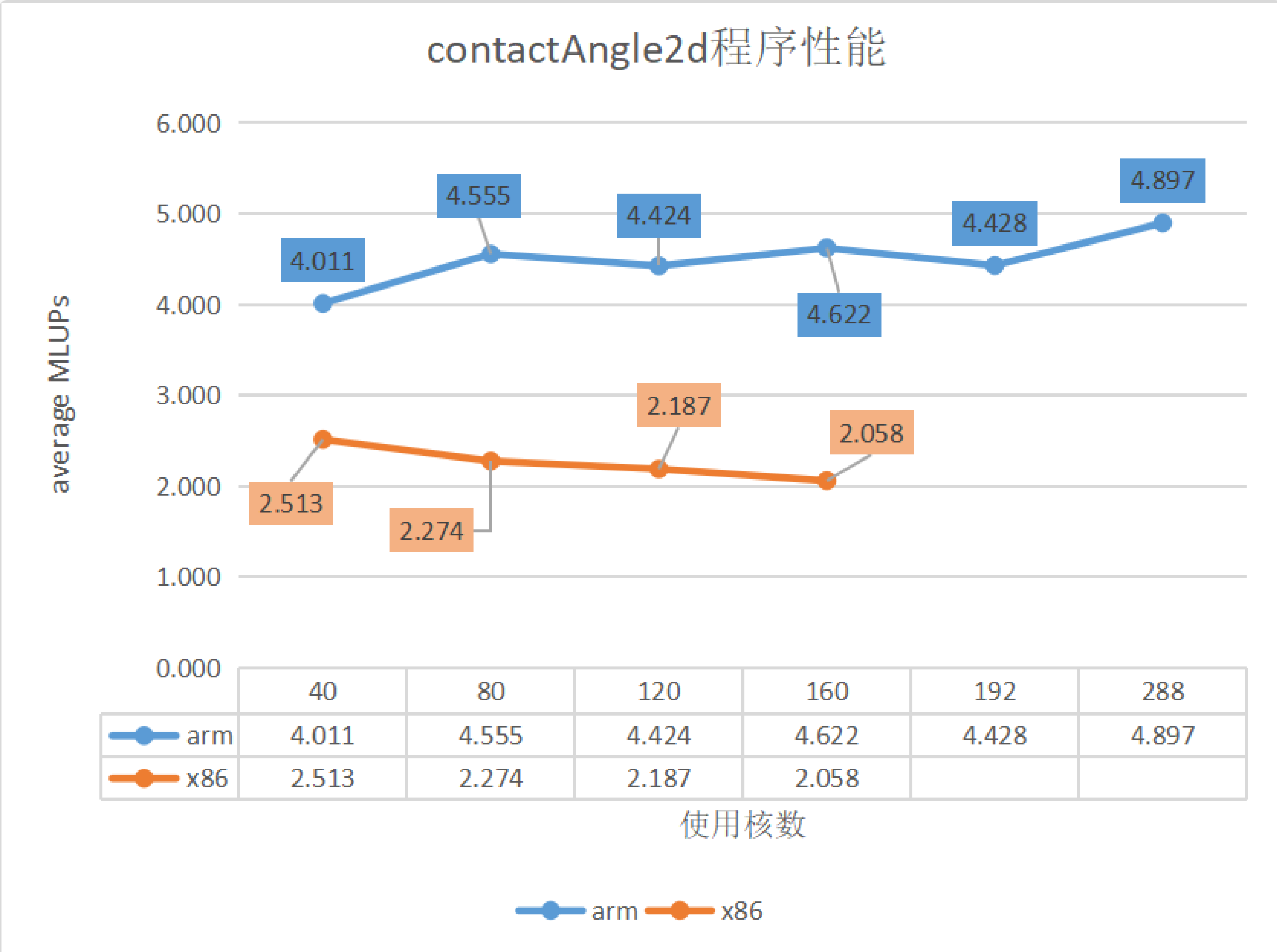
3.6.4 MLUPs程序性能测试

MLUPs指标为百万格子（cell）每秒更新数，该数值越大越好。

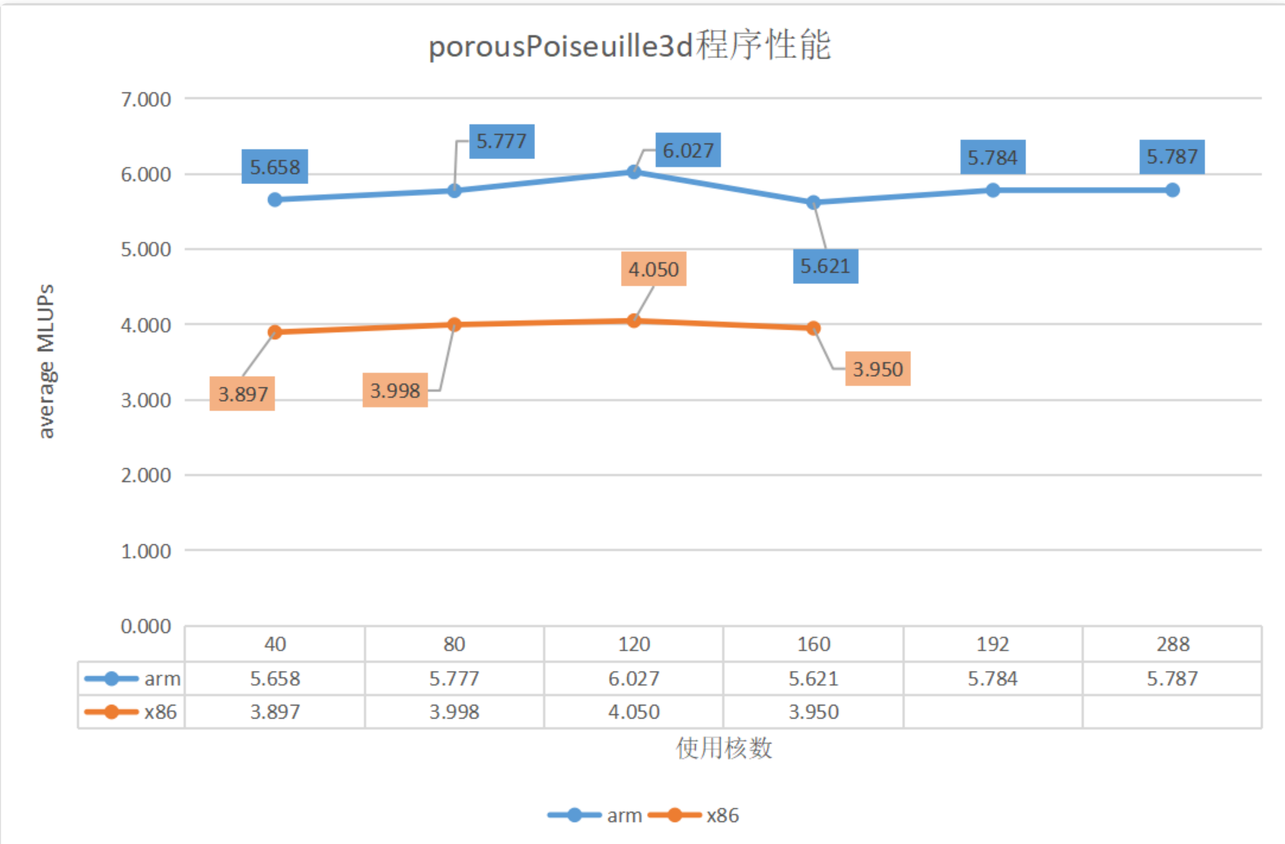


	40	80	120	160	192	288
arm	33.892	47.507	47.716	47.563	48.016	49.205
x86	28.566	40.867	46.172	49.299		

bstesp3d性能



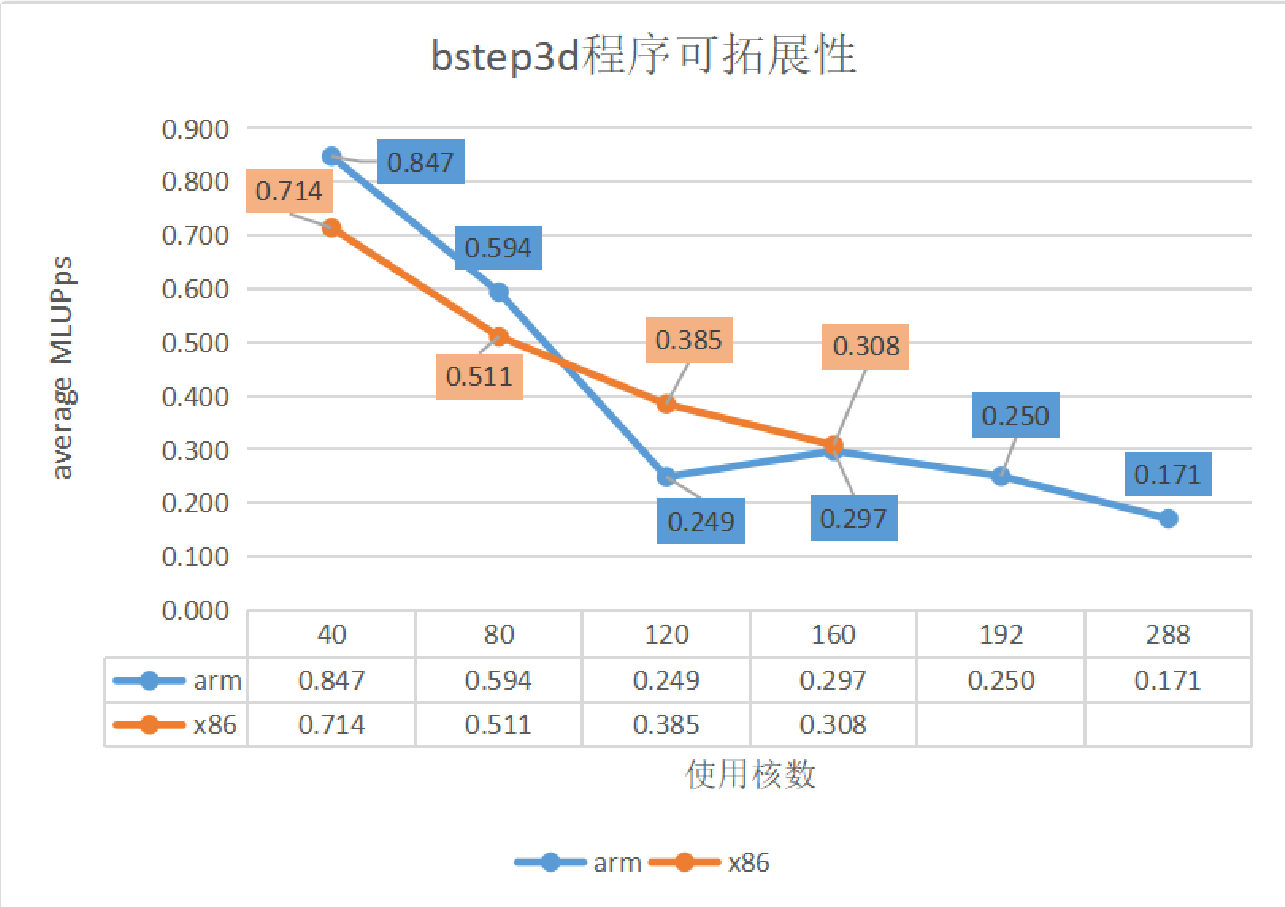
contactAngle2d性能



porousPoiseuille3d性能

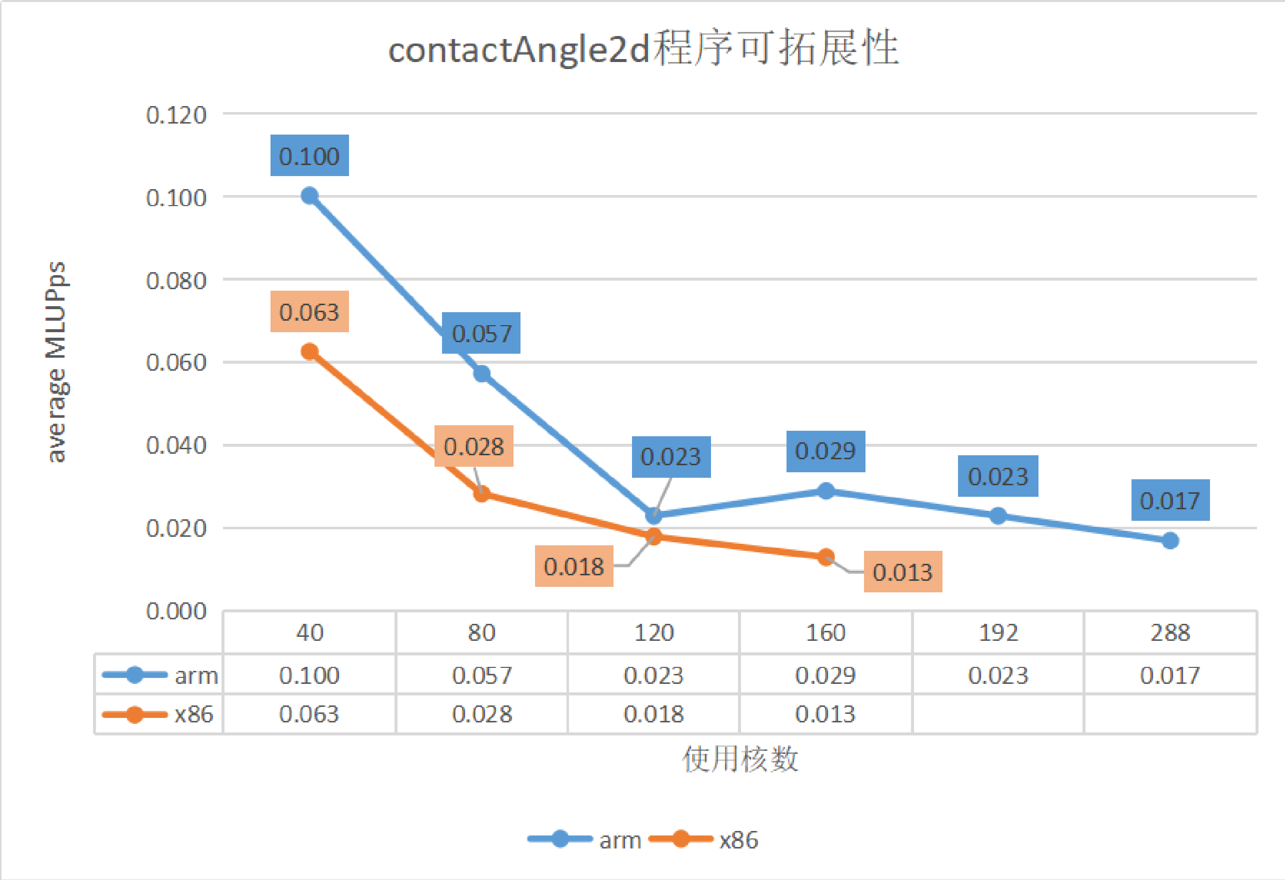
3.6.5 MLUPps可扩展性测试

MLUPps衡量每个计算单元负载的运算量，由于此参数由MLUPs计算得来，只代表能否进行有效的负载均衡。

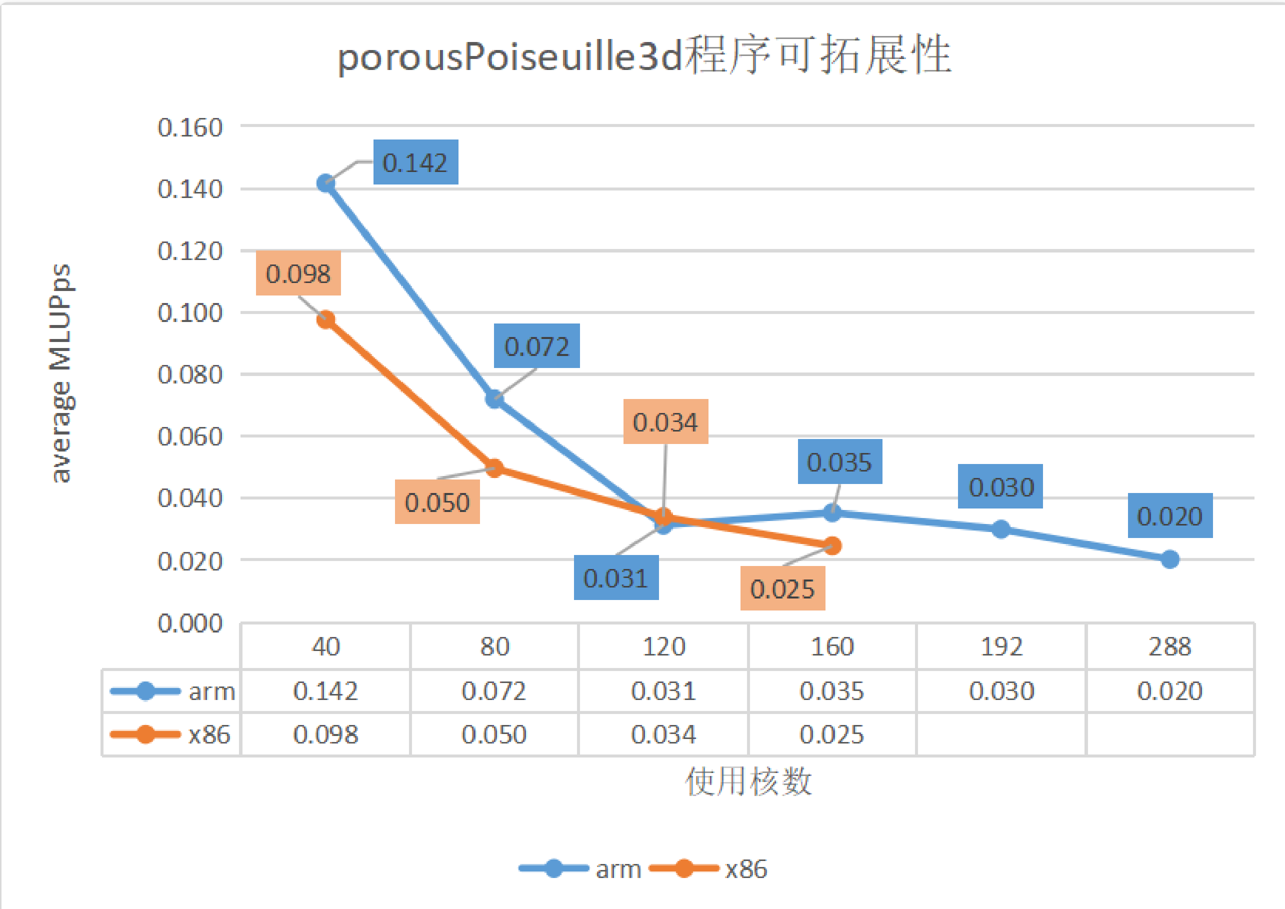


	40	80	120	160	192	288
arm	0.847	0.594	0.249	0.297	0.250	0.171
x86	0.714	0.511	0.385	0.308		

bstesp3d mpi可扩展性



contactAngle2d mpi可扩展性



porousPoiseuille3d mpi可扩展性

3.7 性能测试结论

通过在用户、CPU时间以及LBM指标MLUPs和MLUPps的分析对比，可以看到，在经过充分的优化调优后，基于鲲鹏920集群的openEuler系统上移植的OpenLB应用性能远远超过GCC在x86平台上串行编译运行得到的结果。同时对比Intel集群的CentOS系统，在MLUPs指标上鲲鹏平台平均高 **2 - 5** MLUPs。在可拓展性上鲲鹏平台表现良好，在众核情况下仍能保持住稳定的负载均衡。同时在数据量较小、运行时间短（**contactAngle2d**和**porousPoiseuille3d**）和数据量大、运行时间长（**bstep3d**）的程序上，鲲鹏平台相对Intel平台能保持住稳定的性能提升和拓展性，具有较好的稳定性。

4. 精度测试

4.1 案例程序选择

选择porousPoiseuille3d程序进行精度测试，此仿真程序用于模拟、检测具有多孔介质的 3D 泊肃叶流动。

该程序运行后会在tmp目录下生成对应的gnuplot数据用于绘制图形，数据形式如下：

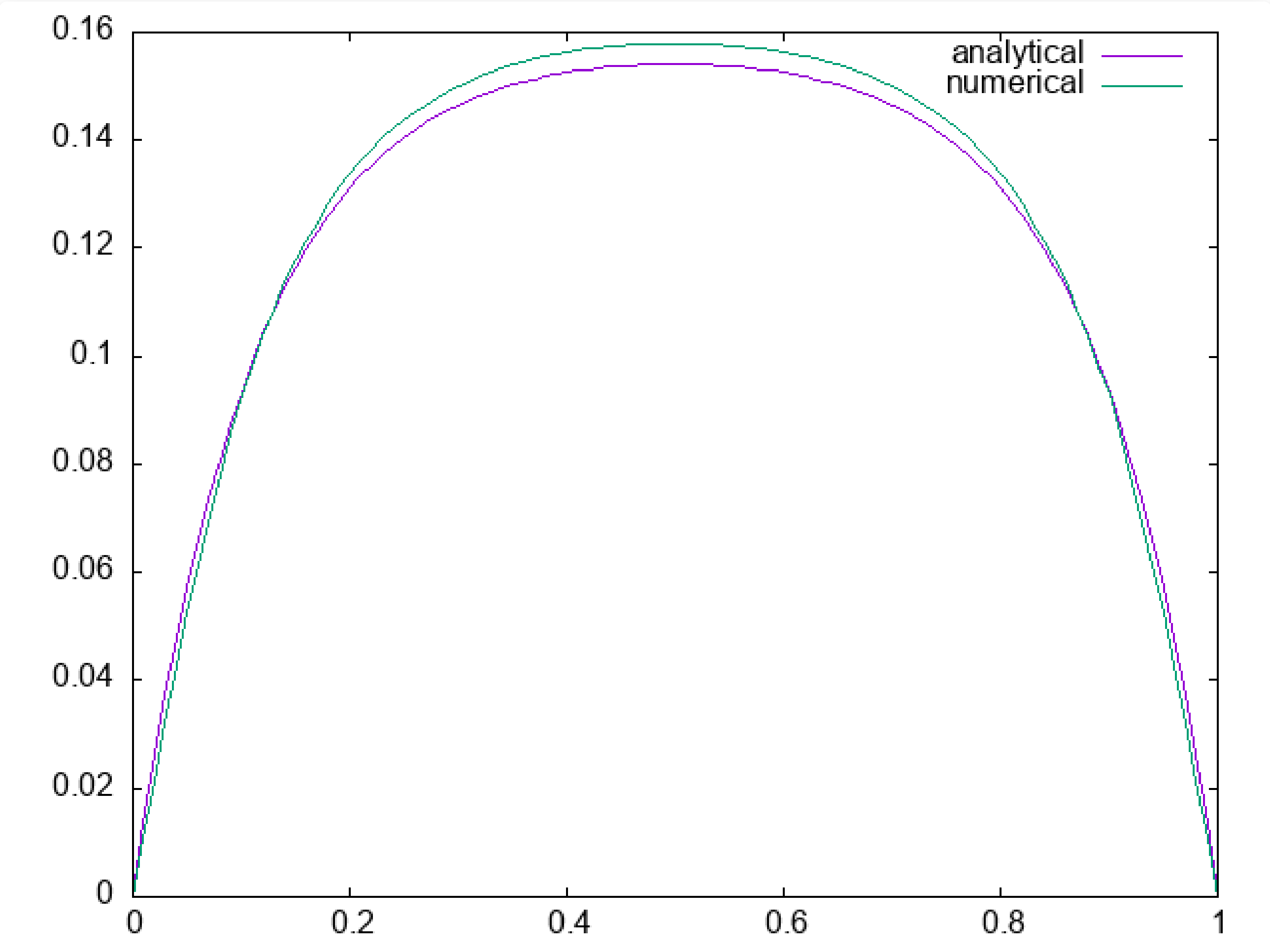
```
0 0 0
0.01 0.0136234 0.01069
0.02 0.026053 0.0213801
0.03 0.0373948 0.0320701
0.04 0.0477452 0.0427601
0.05 0.0571921 0.05288
0.06 0.0658154 0.0611754
0.07 0.0736879 0.0694709
0.08 0.0808759 0.0777663
0.09 0.0874397 0.0860617
0.1 0.0934344 0.0929219
0.11 0.0989099 0.0982035
0.12 0.103912 0.103485
0.13 0.108482 0.108767
0.14 0.112657 0.114048
0.15 0.116473 0.117975
0.16 0.119961 0.121359
0.17 0.123148 0.124744
0.18 0.126062 0.128128
0.19 0.128726 0.131512
0.2 0.131161 0.133749
0.21 0.133388 0.135928
0.22 0.135423 0.138107
0.23 0.137284 0.140285
0.24 0.138986 0.142317
0.25 0.140541 0.14372
0.26 0.141962 0.145123
0.27 0.14326 0.146526
0.28 0.144446 0.147929
0.29 0.145528 0.149116
0.3 0.146516 0.150013
0.31 0.147416 0.150909
0.32 0.148236 0.151806
0.33 0.148982 0.152703
0.34 0.149659 0.153375
```

```
0.35 0.150273 0.153934
0.36 0.150829 0.154493
0.37 0.151329 0.155052
0.38 0.151779 0.155611
0.39 0.152181 0.155958
0.4 0.152539 0.156282
0.41 0.152854 0.156606
0.42 0.153131 0.156931
0.43 0.153369 0.15723
0.44 0.153572 0.157379
0.45 0.153741 0.157528
0.46 0.153878 0.157677
0.47 0.153983 0.157826
0.48 0.154057 0.157918
0.49 0.154101 0.157918
0.5 0.154116 0.157918
0.51 0.154101 0.157918
0.52 0.154057 0.157918
0.53 0.153983 0.157826
0.54 0.153878 0.157677
0.55 0.153741 0.157528
0.56 0.153572 0.15738
0.57 0.153369 0.157231
0.58 0.153131 0.156932
0.59 0.152854 0.156607
0.6 0.152539 0.156283
0.61 0.152181 0.155959
0.62 0.151779 0.155612
0.63 0.151329 0.155053
0.64 0.150829 0.154494
0.65 0.150273 0.153935
0.66 0.149659 0.153376
0.67 0.148982 0.152704
0.68 0.148236 0.151808
0.69 0.147416 0.150911
0.7 0.146516 0.150014
0.71 0.145528 0.149117
0.72 0.144446 0.147931
0.73 0.14326 0.146528
0.74 0.141962 0.145125
0.75 0.140541 0.143721
0.76 0.138986 0.142318
0.77 0.137284 0.140287
0.78 0.135423 0.138108
0.79 0.133388 0.135929
0.8 0.131161 0.13375
0.81 0.128726 0.131514
0.82 0.126062 0.12813
0.83 0.123148 0.124745
0.84 0.119961 0.121361
0.85 0.116473 0.117976
0.86 0.112657 0.11405
0.87 0.108482 0.108768
0.88 0.103912 0.103487
```

```
0.89 0.0989099 0.0982049
0.9 0.0934344 0.0929233
0.91 0.0874397 0.0860629
0.92 0.0808759 0.0777674
0.93 0.0736879 0.0694719
0.94 0.0658154 0.0611763
0.95 0.0571921 0.0528808
0.96 0.0477452 0.0427608
0.97 0.0373948 0.0320706
0.98 0.026053 0.0213804
0.99 0.0136234 0.0106902
1 0 0
```

上述数据第一列为百分比进度，第二列为analytical数值，第三列为numerical数值，为计算得出。此次精度测试使用第三列数值以GCC编译的程序输出为基准进行比较分析。

这些数据通过gnuplot处理输出图片如下：



输出图片 示例

4.2 数据分析

使用编译优化分析时的编译参数，对GCC串行运行、Intel MPI并行版本和OpenEuler系统上的Hyper MPI并行运行的结果进行比较，各个输出结果如下：

- GCC

```
0 0 0
0.01 0.0136234 0.01069
0.02 0.026053 0.02138
0.03 0.0373948 0.03207
0.04 0.0477452 0.04276
0.05 0.0571921 0.0528798
0.06 0.0658154 0.0611752
0.07 0.0736879 0.0694706
0.08 0.0808759 0.077766
0.09 0.0874397 0.0860614
0.1 0.0934344 0.0929216
0.11 0.0989099 0.0982031
0.12 0.103912 0.103485
0.13 0.108482 0.108766
0.14 0.112657 0.114048
0.15 0.116473 0.117974
0.16 0.119961 0.121359
0.17 0.123148 0.124743
0.18 0.126062 0.128128
0.19 0.128726 0.131512
0.2 0.131161 0.133748
0.21 0.133388 0.135927
0.22 0.135423 0.138106
0.23 0.137284 0.140285
0.24 0.138986 0.142316
0.25 0.140541 0.143719
0.26 0.141962 0.145123
0.27 0.14326 0.146526
0.28 0.144446 0.147929
0.29 0.145528 0.149115
0.3 0.146516 0.150012
0.31 0.147416 0.150909
0.32 0.148236 0.151806
0.33 0.148982 0.152703
0.34 0.149659 0.153374
0.35 0.150273 0.153934
0.36 0.150829 0.154493
0.37 0.151329 0.155052
0.38 0.151779 0.155611
0.39 0.152181 0.155958
0.4 0.152539 0.156282
0.41 0.152854 0.156606
0.42 0.153131 0.156931
0.43 0.153369 0.15723
0.44 0.153572 0.157379
0.45 0.153741 0.157528
0.46 0.153878 0.157677
0.47 0.153983 0.157826
0.48 0.154057 0.157918
0.49 0.154101 0.157918
0.5 0.154116 0.157918
0.51 0.154101 0.157918
```

```
0.52 0.154057 0.157918
0.53 0.153983 0.157826
0.54 0.153878 0.157677
0.55 0.153741 0.157528
0.56 0.153572 0.15738
0.57 0.153369 0.157231
0.58 0.153131 0.156932
0.59 0.152854 0.156607
0.6 0.152539 0.156283
0.61 0.152181 0.155959
0.62 0.151779 0.155612
0.63 0.151329 0.155053
0.64 0.150829 0.154494
0.65 0.150273 0.153935
0.66 0.149659 0.153376
0.67 0.148982 0.152705
0.68 0.148236 0.151808
0.69 0.147416 0.150911
0.7 0.146516 0.150014
0.71 0.145528 0.149117
0.72 0.144446 0.147931
0.73 0.14326 0.146528
0.74 0.141962 0.145125
0.75 0.140541 0.143722
0.76 0.138986 0.142318
0.77 0.137284 0.140287
0.78 0.135423 0.138108
0.79 0.133388 0.135929
0.8 0.131161 0.133751
0.81 0.128726 0.131514
0.82 0.126062 0.12813
0.83 0.123148 0.124745
0.84 0.119961 0.121361
0.85 0.116473 0.117976
0.86 0.112657 0.11405
0.87 0.108482 0.108768
0.88 0.103912 0.103487
0.89 0.0989099 0.0982049
0.9 0.0934344 0.0929233
0.91 0.0874397 0.086063
0.92 0.0808759 0.0777674
0.93 0.0736879 0.0694719
0.94 0.0658154 0.0611764
0.95 0.0571921 0.0528808
0.96 0.0477452 0.0427608
0.97 0.0373948 0.0320706
0.98 0.026053 0.0213804
0.99 0.0136234 0.0106902
1 0 0
```

- 鲲鹏920（OpenEuler上的Hyper MPI）

```
0 0 0
0.01 0.0136234 0.01069
0.02 0.026053 0.0213801
0.03 0.0373948 0.0320701
0.04 0.0477452 0.0427601
0.05 0.0571921 0.05288
0.06 0.0658154 0.0611754
0.07 0.0736879 0.0694709
0.08 0.0808759 0.0777663
0.09 0.0874397 0.0860617
0.1 0.0934344 0.0929219
0.11 0.0989099 0.0982035
0.12 0.103912 0.103485
0.13 0.108482 0.108767
0.14 0.112657 0.114048
0.15 0.116473 0.117975
0.16 0.119961 0.121359
0.17 0.123148 0.124744
0.18 0.126062 0.128128
0.19 0.128726 0.131512
0.2 0.131161 0.133749
0.21 0.133388 0.135928
0.22 0.135423 0.138107
0.23 0.137284 0.140285
0.24 0.138986 0.142317
0.25 0.140541 0.14372
0.26 0.141962 0.145123
0.27 0.14326 0.146526
0.28 0.144446 0.147929
0.29 0.145528 0.149116
0.3 0.146516 0.150013
0.31 0.147416 0.150909
0.32 0.148236 0.151806
0.33 0.148982 0.152703
0.34 0.149659 0.153375
0.35 0.150273 0.153934
0.36 0.150829 0.154493
0.37 0.151329 0.155052
0.38 0.151779 0.155611
0.39 0.152181 0.155958
0.4 0.152539 0.156282
0.41 0.152854 0.156606
0.42 0.153131 0.156931
0.43 0.153369 0.15723
0.44 0.153572 0.157379
0.45 0.153741 0.157528
0.46 0.153878 0.157677
0.47 0.153983 0.157826
0.48 0.154057 0.157918
0.49 0.154101 0.157918
0.5 0.154116 0.157918
0.51 0.154101 0.157918
0.52 0.154057 0.157918
```

```
0.53 0.153983 0.157826
0.54 0.153878 0.157677
0.55 0.153741 0.157528
0.56 0.153572 0.15738
0.57 0.153369 0.157231
0.58 0.153131 0.156932
0.59 0.152854 0.156607
0.6 0.152539 0.156283
0.61 0.152181 0.155959
0.62 0.151779 0.155612
0.63 0.151329 0.155053
0.64 0.150829 0.154494
0.65 0.150273 0.153935
0.66 0.149659 0.153376
0.67 0.148982 0.152704
0.68 0.148236 0.151808
0.69 0.147416 0.150911
0.7 0.146516 0.150014
0.71 0.145528 0.149117
0.72 0.144446 0.147931
0.73 0.14326 0.146528
0.74 0.141962 0.145125
0.75 0.140541 0.143721
0.76 0.138986 0.142318
0.77 0.137284 0.140287
0.78 0.135423 0.138108
0.79 0.133388 0.135929
0.8 0.131161 0.13375
0.81 0.128726 0.131514
0.82 0.126062 0.12813
0.83 0.123148 0.124745
0.84 0.119961 0.121361
0.85 0.116473 0.117976
0.86 0.112657 0.11405
0.87 0.108482 0.108768
0.88 0.103912 0.103487
0.89 0.0989099 0.0982049
0.9 0.0934344 0.0929233
0.91 0.0874397 0.0860629
0.92 0.0808759 0.0777674
0.93 0.0736879 0.0694719
0.94 0.0658154 0.0611763
0.95 0.0571921 0.0528808
0.96 0.0477452 0.0427608
0.97 0.0373948 0.0320706
0.98 0.026053 0.0213804
0.99 0.0136234 0.0106902
1 0 0
```

- Intel x86集群（CentOS上的Intel MPI）

```
0 0 0
0.01 0.0136234 0.01069
0.02 0.026053 0.02138
0.03 0.0373948 0.0320701
0.04 0.0477452 0.0427601
0.05 0.0571921 0.0528799
0.06 0.0658154 0.0611753
0.07 0.0736879 0.0694707
0.08 0.0808759 0.0777662
0.09 0.0874397 0.0860616
0.1 0.0934344 0.0929218
0.11 0.0989099 0.0982033
0.12 0.103912 0.103485
0.13 0.108482 0.108766
0.14 0.112657 0.114048
0.15 0.116473 0.117974
0.16 0.119961 0.121359
0.17 0.123148 0.124743
0.18 0.126062 0.128128
0.19 0.128726 0.131512
0.2 0.131161 0.133749
0.21 0.133388 0.135927
0.22 0.135423 0.138106
0.23 0.137284 0.140285
0.24 0.138986 0.142316
0.25 0.140541 0.14372
0.26 0.141962 0.145123
0.27 0.14326 0.146526
0.28 0.144446 0.147929
0.29 0.145528 0.149116
0.3 0.146516 0.150012
0.31 0.147416 0.150909
0.32 0.148236 0.151806
0.33 0.148982 0.152703
0.34 0.149659 0.153375
0.35 0.150273 0.153934
0.36 0.150829 0.154493
0.37 0.151329 0.155052
0.38 0.151779 0.155611
0.39 0.152181 0.155958
0.4 0.152539 0.156282
0.41 0.152854 0.156606
0.42 0.153131 0.156931
0.43 0.153369 0.15723
0.44 0.153572 0.157379
0.45 0.153741 0.157528
0.46 0.153878 0.157677
0.47 0.153983 0.157826
0.48 0.154057 0.157918
0.49 0.154101 0.157918
0.5 0.154116 0.157918
0.51 0.154101 0.157918
0.52 0.154057 0.157918
```

```
0.53 0.153983 0.157826
0.54 0.153878 0.157677
0.55 0.153741 0.157528
0.56 0.153572 0.15738
0.57 0.153369 0.157231
0.58 0.153131 0.156932
0.59 0.152854 0.156607
0.6 0.152539 0.156283
0.61 0.152181 0.155959
0.62 0.151779 0.155612
0.63 0.151329 0.155053
0.64 0.150829 0.154494
0.65 0.150273 0.153935
0.66 0.149659 0.153376
0.67 0.148982 0.152704
0.68 0.148236 0.151807
0.69 0.147416 0.150911
0.7 0.146516 0.150014
0.71 0.145528 0.149117
0.72 0.144446 0.147931
0.73 0.14326 0.146528
0.74 0.141962 0.145124
0.75 0.140541 0.143721
0.76 0.138986 0.142318
0.77 0.137284 0.140287
0.78 0.135423 0.138108
0.79 0.133388 0.135929
0.8 0.131161 0.13375
0.81 0.128726 0.131514
0.82 0.126062 0.128129
0.83 0.123148 0.124745
0.84 0.119961 0.121361
0.85 0.116473 0.117976
0.86 0.112657 0.11405
0.87 0.108482 0.108768
0.88 0.103912 0.103486
0.89 0.0989099 0.0982047
0.9 0.0934344 0.0929231
0.91 0.0874397 0.0860627
0.92 0.0808759 0.0777672
0.93 0.0736879 0.0694717
0.94 0.0658154 0.0611762
0.95 0.0571921 0.0528807
0.96 0.0477452 0.0427607
0.97 0.0373948 0.0320705
0.98 0.026053 0.0213803
0.99 0.0136234 0.0106902
1 0 0
```

以GCC为基准，python测试脚本如下：

```python
armData = []
x86Data = []
defaultData = []

with open("arm.velocityProfile.dat", "r") as armfile:
    for line in armfile:
        armData.append(float(line.replace("\n", "").split(" ").pop()))

with open("x86.velocityProfile.dat", "r") as x86file:
    for line in x86file:
        x86Data.append(float(line.replace("\n", "").split(" ").pop()))

with open("gcc.velocityProfile.dat", "r") as defaultfile:
    for line in defaultfile:
        defaultData.append(float(line.replace("\n", "").split(" ").pop()))

print("arm data: \n" , armData)
print("x86 data: \n" , x86Data)
print("default data: \n" , defaultData)

print("====now print accuracy between arm and gcc data!====")

for i in range(len(armData)):
    try:
        print(abs((armData[i]-defaultData[i]) / defaultData[i]) * 100, '%')
    except ZeroDivisionError:
        print("All zero!")

print("====now print accuracy between x86 and gcc data!====")

for i in range(len(x86Data)):
    try:
        print(abs((x86Data[i]-defaultData[i]) / defaultData[i]) * 100, '%')
    except ZeroDivisionError:
        print("All zero!")
```

运行该脚本（数据已放至正确位置），得到结果:

```
/usr/bin/python3.8 /mnt/data/Git/PortOpenLB/UseOfOpenLB/精度测试/对比文
件/data/accuracy_test.py
arm data:
 [0.0, 0.01069, 0.0213801, 0.0320701, 0.0427601, 0.05288, 0.0611754, 0.0694709,
0.0777663, 0.0860617, 0.0929219, 0.0982035, 0.103485, 0.108767, 0.114048,
0.117975, 0.121359, 0.124744, 0.128128, 0.131512, 0.133749, 0.135928, 0.138107,
0.140285, 0.142317, 0.14372, 0.145123, 0.146526, 0.147929, 0.149116, 0.150013,
0.150909, 0.151806, 0.152703, 0.153375, 0.153934, 0.154493, 0.155052, 0.155611,
0.155958, 0.156282, 0.156606, 0.156931, 0.15723, 0.157379, 0.157528, 0.157677,
0.157826, 0.157918, 0.157918, 0.157918, 0.157918, 0.157918, 0.157826, 0.157677,
0.157528, 0.15738, 0.157231, 0.156932, 0.156607, 0.156283, 0.155959, 0.155612,
0.155053, 0.154494, 0.153935, 0.153376, 0.152704, 0.151808, 0.150911, 0.150014,
0.149117, 0.147931, 0.146528, 0.145125, 0.143721, 0.142318, 0.140287, 0.138108,
```

```
0.135929, 0.13375, 0.131514, 0.12813, 0.124745, 0.121361, 0.117976, 0.11405,
0.108768, 0.103487, 0.0982049, 0.0929233, 0.0860629, 0.0777674, 0.0694719,
0.0611763, 0.0528808, 0.0427608, 0.0320706, 0.0213804, 0.0106902, 0.0]
x86 data:
 [0.0, 0.01069, 0.02138, 0.0320701, 0.0427601, 0.0528799, 0.0611753, 0.0694707,
0.0777662, 0.0860616, 0.0929218, 0.0982033, 0.103485, 0.108766, 0.114048,
0.117974, 0.121359, 0.124743, 0.128128, 0.131512, 0.133749, 0.135927, 0.138106,
0.140285, 0.142316, 0.14372, 0.145123, 0.146526, 0.147929, 0.149116, 0.150012,
0.150909, 0.151806, 0.152703, 0.153375, 0.153934, 0.154493, 0.155052, 0.155611,
0.155958, 0.156282, 0.156606, 0.156931, 0.15723, 0.157379, 0.157528, 0.157677,
0.157826, 0.157918, 0.157918, 0.157918, 0.157918, 0.157918, 0.157826, 0.157677,
0.157528, 0.15738, 0.157231, 0.156932, 0.156607, 0.156283, 0.155959, 0.155612,
0.155053, 0.154494, 0.153935, 0.153376, 0.152704, 0.151807, 0.150911, 0.150014,
0.149117, 0.147931, 0.146528, 0.145124, 0.143721, 0.142318, 0.140287, 0.138108,
0.135929, 0.13375, 0.131514, 0.128129, 0.124745, 0.121361, 0.117976, 0.11405,
0.108768, 0.103486, 0.0982047, 0.0929231, 0.0860627, 0.0777672, 0.0694717,
0.0611762, 0.0528807, 0.0427607, 0.0320705, 0.0213803, 0.0106902, 0.0]
default data:
 [0.0, 0.01069, 0.02138, 0.03207, 0.04276, 0.0528798, 0.0611752, 0.0694706,
0.077766, 0.0860614, 0.0929216, 0.0982031, 0.103485, 0.108766, 0.114048, 0.117974,
0.121359, 0.124743, 0.128128, 0.131512, 0.133748, 0.135927, 0.138106, 0.140285,
0.142316, 0.143719, 0.145123, 0.146526, 0.147929, 0.149115, 0.150012, 0.150909,
0.151806, 0.152703, 0.153374, 0.153934, 0.154493, 0.155052, 0.155611, 0.155958,
0.156282, 0.156606, 0.156931, 0.15723, 0.157379, 0.157528, 0.157677, 0.157826,
0.157918, 0.157918, 0.157918, 0.157918, 0.157918, 0.157826, 0.157677, 0.157528,
0.15738, 0.157231, 0.156932, 0.156607, 0.156283, 0.155959, 0.155612, 0.155053,
0.154494, 0.153935, 0.153376, 0.152705, 0.151808, 0.150911, 0.150014, 0.149117,
0.147931, 0.146528, 0.145125, 0.143722, 0.142318, 0.140287, 0.138108, 0.135929,
0.133751, 0.131514, 0.12813, 0.124745, 0.121361, 0.117976, 0.11405, 0.108768,
0.103487, 0.0982049, 0.0929233, 0.086063, 0.0777674, 0.0694719, 0.0611764,
0.0528808, 0.0427608, 0.0320706, 0.0213804, 0.0106902, 0.0]
====now print accuracy between arm and gcc data!====
All zero!
0.0 %
0.00046772684751827 %
0.000311817898334695 %
0.00023386342376724873 %
0.0003782162565020124 %
0.0003269298670029885 %
0.0004318373527918669 %
0.00038577270271680287 %
0.00034858833345568016 %
0.00032285281356393637 %
0.0004073191172148582 %
0.0 %
0.0009194049611100896 %
0.0 %
0.0008476443962237443 %
0.0 %
0.0008016481886655942 %
0.0 %
0.0 %
0.0007476747315855191 %
0.0007356890095426223 %
```

```
0.0007240815026146583 %
0.0 %
0.0007026616824538352 %
0.0006958022251568994 %
0.0 %
0.0 %
0.0 %
0.0006706233443992892 %
0.0006666133376003253 %
0.0 %
0.0 %
0.0 %
0.0006520009910421584 %
0.0 %
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0.0006548574048007597 %
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0.0 %
0.0 %
0.0 %
0.0 %
0.0 %
0.0 %
0.0006957877012572885 %
```

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0.0 %
0.0 %
0.0 %
0.00074765796143655 %
0.0 %
0.0 %
0.0 %
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0.0 %
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0.0 %
0.0 %
0.0 %
0.00011619395094625515 %
0.0 %
0.0 %
0.00016346172706458155 %
0.0 %
0.0 %
0.0 %
0.0 %
0.0 %
All zero!
====now print accuracy between x86 and gcc data!====
All zero!
0.0 %
0.0 %
0.000311817898334695 %
0.00023386342376724873 %
0.0001891081282510062 %
0.0001634649335071656 %
0.00014394578426395565 %
0.00025718180180525337 %
0.00023239222230378675 %
0.00021523520904262426 %
0.00020365955860036325 %
0.0 %
0.0 %
0.0 %
0.0 %
0.0 %
0.0 %
0.0 %
0.0 %
0.0007476747315855191 %
0.0 %
0.0 %
0.0 %
0.0 %
0.0006958022251568994 %
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```

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0.0006706233443992892 %
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0.0006890611541781223 %
0.0006957877012572885 %
0.0 %
0.0 %
0.0 %
0.0 %
0.00074765796143655 %
0.0 %
```

```
0.000780457348006712 %
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0.0 %
0.0 %
0.0009663049465159875 %
0.00020365582571936163 %
0.0002152312713880707 %
0.0003485818528226403 %
0.00025717717193290653 %
0.00028788618132763195 %
0.00032692345414050554 %
0.00018910455211709482 %
0.00023385904848102833 %
0.00031181206461973487 %
0.00046771809694582945 %
0.0 %
All zero!

进程已结束,退出代码0
```

4.3 分析结果

经过分析，所有误差均小于1%，编译结果通过测试。