



1
00:00:15,709 --> 00:00:13,910
with the advent of space technology new

2
00:00:18,080 --> 00:00:15,719
opportunities are emerging for

3
00:00:21,080 --> 00:00:18,090
scientific research with exciting

4
00:00:23,060 --> 00:00:21,090
applications in many fields to take

5
00:00:26,000 --> 00:00:23,070
advantage of this new era in space

6
00:00:27,800 --> 00:00:26,010
exploration basic research into the

7
00:00:30,220 --> 00:00:27,810
fundamental characteristics of the

8
00:00:32,889 --> 00:00:30,230
environment of space such as long-term

9
00:00:37,130 --> 00:00:32,899
microgravity and ultra-high vacuum

10
00:00:39,170 --> 00:00:37,140
should first be undertaken the purpose

11
00:00:41,330 --> 00:00:39,180
of the research presented in this video

12
00:00:44,000 --> 00:00:41,340
is to understand more clearly the

13
00:00:46,850 --> 00:00:44,010

effects of surface tension on fluid

14

00:00:49,760 --> 00:00:46,860

convection the predominance of surface

15

00:00:52,459 --> 00:00:49,770

tension effects over buoyancy effects is

16

00:00:55,160 --> 00:00:52,469

a unique characteristic of microgravity

17

00:00:58,099 --> 00:00:55,170

environments and is critically important

18

00:01:00,349 --> 00:00:58,109

to many microgravity applications such

19

00:01:04,039 --> 00:01:00,359

as material processing and fluid

20

00:01:06,590 --> 00:01:04,049

management the fluid system chosen for

21

00:01:09,380 --> 00:01:06,600

this study the liquid sessile droplet

22

00:01:11,840 --> 00:01:09,390

has been selected because among many

23

00:01:14,600 --> 00:01:11,850

fluid systems most affected by surface

24

00:01:16,640 --> 00:01:14,610

tension liquid droplets are particularly

25

00:01:20,660 --> 00:01:16,650

important to many industrial and

26
00:01:22,969 --> 00:01:20,670
biological processes evaporation induced

27
00:01:25,520 --> 00:01:22,979
surface tension effects on liquid

28
00:01:28,730 --> 00:01:25,530
droplets and their associated transport

29
00:01:31,149 --> 00:01:28,740
process can significantly enhance heat

30
00:01:33,679 --> 00:01:31,159
and mass transfer

31
00:01:36,710 --> 00:01:33,689
they are also critical to a wide range

32
00:01:39,260 --> 00:01:36,720
of technologies such as single crystal

33
00:01:41,990 --> 00:01:39,270
growth the spray drying and cooling of

34
00:01:44,649 --> 00:01:42,000
metal and the advanced droplet radiators

35
00:01:47,690 --> 00:01:44,659
of the space stations power systems

36
00:01:50,359 --> 00:01:47,700
while quantitative research on surface

37
00:01:51,830 --> 00:01:50,369
tension induced flow is pivotal to our

38
00:01:54,469 --> 00:01:51,840

understanding of the microgravity

39

00:01:57,800 --> 00:01:54,479

environment it is difficult to achieve

40

00:01:59,929 --> 00:01:57,810

on earth not only do surface tension

41

00:02:02,569 --> 00:01:59,939

driven flow phenomena take place solely

42

00:02:04,429 --> 00:02:02,579

in small-scale systems under normal

43

00:02:07,550 --> 00:02:04,439

gravity surface tension properties

44

00:02:09,699 --> 00:02:07,560

themselves are very easily disturbed by

45

00:02:13,190 --> 00:02:09,709

experimental observation

46

00:02:15,559 --> 00:02:13,200

thus computational simulations

47

00:02:18,140 --> 00:02:15,569

offer an attractive way to investigate

48

00:02:21,110 --> 00:02:18,150

internal convection within liquid

49

00:02:23,360 --> 00:02:21,120

droplets during this video a

50

00:02:25,880 --> 00:02:23,370

cross-sectional representation of the

51
00:02:29,089 --> 00:02:25,890
hemispherical liquid droplet under ideal

52
00:02:32,990 --> 00:02:29,099
conditions is used to show internal

53
00:02:35,300 --> 00:02:33,000
fluid motion the droplet is placed on an

54
00:02:37,910 --> 00:02:35,310
unheated plate with evaporation

55
00:02:40,009 --> 00:02:37,920
occurring along the free surface the

56
00:02:43,280 --> 00:02:40,019
black dots within the liquid droplet are

57
00:02:46,490 --> 00:02:43,290
fluid tracers used to visualize fluid

58
00:02:50,210 --> 00:02:46,500
flow because the processes that occur

59
00:02:52,339 --> 00:02:50,220
are assumed symmetric with respect to

60
00:02:54,770 --> 00:02:52,349
the centerline we will be describing

61
00:02:58,699 --> 00:02:54,780
only the flow field in the right half of

62
00:03:01,250 --> 00:02:58,709
the droplet two types of evaporation

63
00:03:03,920 --> 00:03:01,260

induced convection are presented one

64

00:03:06,470 --> 00:03:03,930

under normal gravity where buoyancy is

65

00:03:09,199 --> 00:03:06,480

the most significant force the other

66

00:03:11,930 --> 00:03:09,209

under microgravity where buoyancy force

67

00:03:15,500 --> 00:03:11,940

subsides and surface tension effects

68

00:03:17,140 --> 00:03:15,510

predominate the patterns of flow that

69

00:03:20,050 --> 00:03:17,150

described them were obtained

70

00:03:23,210 --> 00:03:20,060

computationally using an Adi scheme

71

00:03:25,879 --> 00:03:23,220

while a runga cotta scheme tracks the

72

00:03:28,160 --> 00:03:25,889

motion of the fluid tracers the

73

00:03:34,430 --> 00:03:28,170

calculations required about one hour of

74

00:03:36,559 --> 00:03:34,440

CPU time on the Cray XMP 24in buoyancy

75

00:03:39,410 --> 00:03:36,569

induced convection otherwise known as

76

00:03:43,210 --> 00:03:39,420

Rayleigh convection gravity is the

77

00:03:46,039 --> 00:03:43,220

dominant force in stratified fluids

78

00:03:49,190 --> 00:03:46,049

stability exists when heavier fluids

79

00:03:51,140 --> 00:03:49,200

live beneath lighter fluids that is why

80

00:03:53,660 --> 00:03:51,150

when a heavier fluid lies above a

81

00:03:56,210 --> 00:03:53,670

lighter one the heavier fluid will tend

82

00:03:59,000 --> 00:03:56,220

to descend when the criteria for

83

00:04:03,220 --> 00:03:59,010

stability are exceeded the result will

84

00:04:06,440 --> 00:04:03,230

be fluid motion induced by gravity we

85

00:04:08,750 --> 00:04:06,450

begin with a liquid droplet having a

86

00:04:11,240 --> 00:04:08,760

uniform temperature shown in orange

87

00:04:14,150 --> 00:04:11,250

which is the same as the plate upon

88

00:04:16,759 --> 00:04:14,160

which it rests as evaporative cooling

89

00:04:19,150 --> 00:04:16,769

occurs along the free surface of the

90

00:04:22,009 --> 00:04:19,160

drop the temperature of that surface

91

00:04:26,600 --> 00:04:22,019

decreases which makes the fluid there

92

00:04:29,450 --> 00:04:26,610

heavier as evaporation proceeds the

93

00:04:32,029 --> 00:04:29,460

temperature continues to decrease and a

94

00:04:35,209 --> 00:04:32,039

yellow rim representing the colder fluid

95

00:04:37,490 --> 00:04:35,219

at the surface broadens eventually as

96

00:04:41,240 --> 00:04:37,500

the fluid turns even colder the rim

97

00:04:44,240 --> 00:04:41,250

becomes green and then blue as this

98

00:04:46,580 --> 00:04:44,250

increasingly heavier fluid descends the

99

00:04:49,760 --> 00:04:46,590

relatively warmer fluid of the interior

100

00:04:53,209 --> 00:04:49,770

ascends setting up a clockwise fluid

101
00:04:56,450 --> 00:04:53,219
convection because buoyancy force is a

102
00:04:59,209 --> 00:04:56,460
body force it induces a global motion

103
00:05:02,689 --> 00:04:59,219
and convection occurs almost everywhere

104
00:05:05,089 --> 00:05:02,699
within the liquid drop after an

105
00:05:08,330 --> 00:05:05,099
initially rapid flow the rate of

106
00:05:10,010 --> 00:05:08,340
convection gradually slows down as the

107
00:05:12,920 --> 00:05:10,020
temperature field becomes vertically

108
00:05:15,409 --> 00:05:12,930
more stable the clockwise fluid motion

109
00:05:18,350 --> 00:05:15,419
in the upper layer is reduced and it

110
00:05:26,390 --> 00:05:18,360
almost still predominantly lateral

111
00:05:28,790 --> 00:05:26,400
motion results eventually however as

112
00:05:30,730 --> 00:05:28,800
evaporative cooling continues to reduce

113
00:05:33,680 --> 00:05:30,740

the temperature at the surface a

114

00:05:37,159 --> 00:05:33,690

coupling between internal convection and

115

00:05:38,439 --> 00:05:37,169

that cooling induces to thermal

116

00:05:41,450 --> 00:05:38,449

stratifications

117

00:05:44,200 --> 00:05:41,460

the first stratification moves clockwise

118

00:05:47,659 --> 00:05:44,210

at the lower edge of the droplet surface

119

00:05:49,999 --> 00:05:47,669

the second moves counterclockwise and

120

00:05:52,790 --> 00:05:50,009

begins at the top of the surface as

121

00:05:56,059 --> 00:05:52,800

another vortex of cooler fluid moves

122

00:05:58,339 --> 00:05:56,069

downward into the interior demonstrating

123

00:06:03,159 --> 00:05:58,349

that evaporation induced buoyancy

124

00:06:06,709 --> 00:06:03,169

convection is a dynamic unsteady process

125

00:06:09,110 --> 00:06:06,719

unlike buoyancy dominant flow surface

126
00:06:12,469 --> 00:06:09,120
tension dominant flow has not been well

127
00:06:15,010 --> 00:06:12,479
studied however we do know that it is

128
00:06:19,579 --> 00:06:15,020
partly a function of temperature and

129
00:06:21,649 --> 00:06:19,589
concentration the present study focuses

130
00:06:24,800 --> 00:06:21,659
on the effect of temperature on surface

131
00:06:28,129 --> 00:06:24,810
tension the warmer the fluid the weaker

132
00:06:30,379 --> 00:06:28,139
the surface tension and conversely the

133
00:06:34,129 --> 00:06:30,389
colder the fluid the stronger the

134
00:06:36,290 --> 00:06:34,139
surface tension again we begin with a

135
00:06:38,540 --> 00:06:36,300
liquid droplet having a uniform

136
00:06:40,310 --> 00:06:38,550
temperature which is the same as the

137
00:06:44,120 --> 00:06:40,320
plate upon which it rests

138
00:06:46,610 --> 00:06:44,130

as evaporative cooling occurs along the

139

00:06:49,310 --> 00:06:46,620

droplets free surface the temperature

140

00:06:52,100 --> 00:06:49,320

there decreases shown here by the

141

00:06:55,360 --> 00:06:52,110

broadening yellow rim and it's gradual

142

00:06:57,800 --> 00:06:55,370

transformation from yellow to green

143

00:07:00,200 --> 00:06:57,810

because the temperature at the bottom of

144

00:07:02,690 --> 00:07:00,210

the plate is still warm a temperature

145

00:07:05,060 --> 00:07:02,700

gradient begins to form where the plate

146

00:07:08,090 --> 00:07:05,070

meets the lower edge of the relatively

147

00:07:10,910 --> 00:07:08,100

colder droplet the surface tension is

148

00:07:13,540 --> 00:07:10,920

weakest near the warm plate but stronger

149

00:07:15,950 --> 00:07:13,550

at the colder surface as a result

150

00:07:18,560 --> 00:07:15,960

surface tension is able to pull the

151
00:07:21,500 --> 00:07:18,570
fluid upwards that is away from the

152
00:07:26,090 --> 00:07:21,510
plate and fluid viscosity transfers

153
00:07:28,190 --> 00:07:26,100
momentum into the interior conservation

154
00:07:31,820 --> 00:07:28,200
of mass dictates that a circular

155
00:07:34,640 --> 00:07:31,830
counterclockwise motion or vortex wraps

156
00:07:38,780 --> 00:07:34,650
cold fluid into the interior of the drop

157
00:07:41,750 --> 00:07:38,790
to form a cold pocket the end result is

158
00:07:44,300 --> 00:07:41,760
a self propelling process with a maximum

159
00:07:47,390 --> 00:07:44,310
velocity and the largest temperature

160
00:07:49,370 --> 00:07:47,400
gradient coupled in the cold pocket to

161
00:07:52,310 --> 00:07:49,380
maintain the surface tension induced

162
00:07:55,780 --> 00:07:52,320
fluid flow which pushes the vortex all

163
00:07:59,150 --> 00:07:55,790

the way up the droplets free surface

164

00:08:00,940 --> 00:07:59,160

let's compare our computational results

165

00:08:04,840 --> 00:08:00,950

with what we observe experimentally

166

00:08:08,120 --> 00:08:04,850

using laser shadowgraph

167

00:08:10,820 --> 00:08:08,130

traces of aluminum particles allow us to

168

00:08:14,660 --> 00:08:10,830

visualize evaporation induced convective

169

00:08:17,030 --> 00:08:14,670

patterns inside a chloroform drop a few

170

00:08:21,470 --> 00:08:17,040

seconds after it was placed on an

171

00:08:24,950 --> 00:08:21,480

isothermal plate for regions of flow can

172

00:08:28,100 --> 00:08:24,960

be identified region 1 located at the

173

00:08:31,130 --> 00:08:28,110

top of the drop is stagnant region 2

174

00:08:35,180 --> 00:08:31,140

consists of weak clockwise convection

175

00:08:37,300 --> 00:08:35,190

currents driven by buoyancy force region

176

00:08:41,540 --> 00:08:37,310

3 is composed of a few layers of

177

00:08:44,290 --> 00:08:41,550

hexagonal flow cells finally region 4

178

00:08:46,910 --> 00:08:44,300

has relatively stronger counterclockwise

179

00:08:49,520 --> 00:08:46,920

convection currents which according to

180

00:08:53,330 --> 00:08:49,530

our computational results are driven by

181

00:08:54,020 --> 00:08:53,340

surface tension since the liquid drop is

182

00:08:56,990 --> 00:08:54,030

a small

183

00:08:59,090 --> 00:08:57,000

system surface tension is expected to

184

00:09:01,820 --> 00:08:59,100

play a dominant role in the evaporation

185

00:09:05,150 --> 00:09:01,830

process and this is also what we observe

186

00:09:08,210 --> 00:09:05,160

experimentally as evaporation proceeds

187

00:09:10,160 --> 00:09:08,220

the weak buoyancy induced flow region

188

00:09:13,120 --> 00:09:10,170

shrinks while a counter clockwise

189

00:09:17,090 --> 00:09:13,130

surface tension flow in Region four

190

00:09:19,340 --> 00:09:17,100

displaces Region three upwards this is

191

00:09:21,110 --> 00:09:19,350

exactly the result we saw earlier in the

192

00:09:24,350 --> 00:09:21,120

graphical presentation of surface

193

00:09:26,990 --> 00:09:24,360

tension dominant convection thus the

194

00:09:30,430 --> 00:09:27,000

computational results qualitatively

195

00:09:33,590 --> 00:09:30,440

match the experimental results well

196

00:09:36,740 --> 00:09:33,600

however the observations also reveal a

197

00:09:38,870 --> 00:09:36,750

drawback of the experimental method not

198

00:09:41,180 --> 00:09:38,880

only is the stagnant nature of region

199

00:09:43,880 --> 00:09:41,190

one exaggerated by the particles of

200

00:09:46,160 --> 00:09:43,890

aluminum that accumulate there but the

201
00:09:49,180 --> 00:09:46,170
accumulation eventually destroys the

202
00:09:51,650 --> 00:09:49,190
surface tension properties altogether

203
00:09:54,620 --> 00:09:51,660
let's review the graphical presentation

204
00:09:57,530 --> 00:09:54,630
of buoyancy dominant and thermo

205
00:10:00,260 --> 00:09:57,540
capillary dominant convection using

206
00:10:02,330 --> 00:10:00,270
numerical methods the elapsed time

207
00:10:04,430 --> 00:10:02,340
during this segment of the video will

208
00:10:08,180 --> 00:10:04,440
more accurately reflect real time

209
00:10:10,850 --> 00:10:08,190
processes in buoyancy dominant

210
00:10:14,030 --> 00:10:10,860
convection gravity is the dominant force

211
00:10:16,540 --> 00:10:14,040
as evaporation occurs the temperature at

212
00:10:19,580 --> 00:10:16,550
the droplet surface decreases a

213
00:10:22,060 --> 00:10:19,590

clockwise convection results as the

214

00:10:25,180 --> 00:10:22,070

increasingly colder and heavier fluid

215

00:10:28,190 --> 00:10:25,190

descends and the relatively warmer fluid

216

00:10:30,800 --> 00:10:28,200

ascends eventually as the rate of

217

00:10:33,740 --> 00:10:30,810

convection slows down the clockwise

218

00:10:36,470 --> 00:10:33,750

fluid motion is reduced and lateral

219

00:10:42,860 --> 00:10:36,480

motion predominates until a second

220

00:10:45,080 --> 00:10:42,870

counter clockwise motion begins when we

221

00:10:47,210 --> 00:10:45,090

observe the surface tension dominant

222

00:10:49,880 --> 00:10:47,220

flow characteristics of microgravity

223

00:10:52,850 --> 00:10:49,890

environments a different pattern of

224

00:10:54,920 --> 00:10:52,860

convection occurs the resulting fluid

225

00:10:57,230 --> 00:10:54,930

motion is generated by the surface

226

00:11:00,140 --> 00:10:57,240

tension gradient along the droplet

227

00:11:03,590 --> 00:11:00,150

surface which pulls the fluid upward in

228

00:11:06,200 --> 00:11:03,600

a circular counterclockwise motion the

229

00:11:07,940 --> 00:11:06,210

end result is a self propelling process

230

00:11:10,490 --> 00:11:07,950

with velocity and ten

231

00:11:14,750 --> 00:11:10,500

coupled to maintain the surface tension

232

00:11:16,940 --> 00:11:14,760

induced flow in this video we have seen

233

00:11:20,060 --> 00:11:16,950

a direct simulation of natural

234

00:11:22,970 --> 00:11:20,070

convection inside liquid droplets caused

235

00:11:24,920 --> 00:11:22,980

by evaporative cooling of the two

236

00:11:27,470 --> 00:11:24,930

mechanisms that induce convection

237

00:11:30,200 --> 00:11:27,480

the first was gravitational buoyancy

238

00:11:33,050 --> 00:11:30,210

force and the resulting fluid transport

239

00:11:35,510 --> 00:11:33,060

the well studied rayleigh natural

240

00:11:37,310 --> 00:11:35,520

convection the other mechanism which is

241

00:11:39,560 --> 00:11:37,320

less familiar to the thermal fluid

242

00:11:42,860 --> 00:11:39,570

society but more relevant to future

243

00:11:45,320 --> 00:11:42,870

space venture is surface tension induced

244

00:11:48,350 --> 00:11:45,330

by a thermal gradient and the resulting

245

00:11:51,680 --> 00:11:48,360

fluid motion the so called Marangoni or

246

00:11:53,420 --> 00:11:51,690

thermo capillary convection the

247

00:11:55,340 --> 00:11:53,430

fundamental difference is between these

248

00:11:59,210 --> 00:11:55,350

two convection patterns can be briefly

249

00:12:02,300 --> 00:11:59,220

summarized as follows gravitational

250

00:12:05,150 --> 00:12:02,310

buoyancy force is a body force thus the

251
00:12:07,340 --> 00:12:05,160
induced fluid dynamics is global and the

252
00:12:10,940 --> 00:12:07,350
resulting temperature field in the fluid

253
00:12:13,460 --> 00:12:10,950
is more homogeneous li mixed thermo

254
00:12:16,130 --> 00:12:13,470
capillary force is a surface force and

255
00:12:18,290 --> 00:12:16,140
here both the induced fluid motion and

256
00:12:23,210 --> 00:12:18,300
the thermal stratification is more

257
00:12:26,090 --> 00:12:23,220
intensified along the free surface under

258
00:12:27,980 --> 00:12:26,100
conditions of decreasing gravity the

259
00:12:30,070 --> 00:12:27,990
pattern of fluid flow will gradually

260
00:12:33,410 --> 00:12:30,080
become less dominated by buoyancy

261
00:12:35,320 --> 00:12:33,420
convection eventually when the force of

262
00:12:37,940 --> 00:12:35,330
gravity has been reduced significantly

263
00:12:42,980 --> 00:12:37,950

the flow pattern will be dominated by

264

00:12:44,840 --> 00:12:42,990

surface tension this research video has

265

00:12:47,240 --> 00:12:44,850

illustrated the clear differences

266

00:12:50,150 --> 00:12:47,250

between two mechanisms of fluid

267

00:12:53,750 --> 00:12:50,160

transport thermo capillary convection

268

00:12:56,330 --> 00:12:53,760

and buoyancy dominant convection in the

269

00:12:58,730 --> 00:12:56,340

future the investigator will expand his

270

00:13:00,980 --> 00:12:58,740

studies of fluid flow to explore the

271

00:13:03,860 --> 00:13:00,990

effects of surface tension on double

272

00:13:07,490 --> 00:13:03,870

diffusion and two phase related problems

273

00:13:09,140 --> 00:13:07,500

such as crystal growth he will also

274

00:13:11,330 --> 00:13:09,150

explore the potential of thermo

275

00:13:13,610 --> 00:13:11,340

capillary convection for the droplet

276

00:13:16,960 --> 00:13:13,620

radiators involved in the Space

277

00:13:19,400 --> 00:13:16,970

Station's power system such

278

00:13:21,740 --> 00:13:19,410

computational studies are laying the

279

00:13:24,070 --> 00:13:21,750

groundwork that will enable NASA

280

00:13:27,140 --> 00:13:24,080

and its partners in academia and

281

00:13:30,080 --> 00:13:27,150

industry to design the expensive

282

00:13:34,340 --> 00:13:30,090

experimental ventures in outer space of

283

00:13:36,740 --> 00:13:34,350

the coming decade together numerical and

284

00:13:38,900 --> 00:13:36,750

experimental studies we'll be able to

285

00:13:41,270 --> 00:13:38,910

meet the challenge of exploiting the

286

00:13:43,790 --> 00:13:41,280

revolutionary capabilities the space

287

00:13:46,550 --> 00:13:43,800

station offers thus helping to fulfill