Nanofluid Flow Effects on Metal Surfaces

This work presents an experimental study on possible surface damage (erosion, corrosion and abrasion) when water flow is replaced with nanofluid flow, i.e, a water suspension of nanometer-sized solid particle materials used for possible heat transfer enhancement. Experimental data is obtained with a test rig built in the laboratories of the Technical Unit for Advanced Technologies for Energy and Industry of ENEA. Erosion tests have been conducted on aluminium, copper, and stainless steel targets, using the following nanofluids: TiO_2, Al_2O_3, SiC, ZrO_2 and the base fluid of ZrO_2

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Effetto del flusso di nanofluidi su superfici metalliche

Questo lavoro presenta uno studio sperimentale circa il possibile danneggiamento di superfici di componenti (per erosione, corrosione e abrasione) quando l'acqua è sostituita con un nanofluido, cioè una sospensione di particelle solide di dimensioni nanometriche, ai fini di potenziali miglioramenti delle prestazioni termiche. I dati sono ottenuti con un impianto sperimentale costruito nei laboratori dell'Unità tecnica Tecnologie Avanzate per l'Energia e l'Industria dell'ENEA. I test di erosione sono stati condotti su provini di alluminio, rame e acciaio inossidabile, usando i seguenti nanofluidi: TiO_2, Al_2O_3, SiC, ZrO_2 e il suo fluido-base

Introduction

Historical attempts to achieve higher heat transfer rates, adding particles in the order of millimeters or even micrometers, have encountered problems. Suspensions with millimeter- or micron-sized particles are known to cause severe problems in heat transfer equipment. In particular, large particles tend to quickly settle out of suspension and cause severe clogging by passing through micro channels. Thereby, the pressure drop increases considerably. Furthermore, the abrasive actions of the particles cause the erosion of industrial components and pipe lines.

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In more recent years the international research community has shown significant interest in investigating nanofluids (particle size less than 100 nm) to be used as heat transfer fluids or coolants. Several review papers are available in this field with regards to thermal enhancement [1-5], sometimes reporting also the presence of sparse and inconsistent and/or contradictory experimental results from different laboratories [2,3].

About the mechanical effects (erosion, abrasion, corrosion) of nanofluids, smaller effects are expected, but no publication of robust experimental data and analysis on this topic is available hitherto. Since this knowledge is of vital importance with regard to both com-

mercialisation of nanofluid coolants and the research community, experimental data about nanofluid mechanical effects on components is necessary for industrial adoption of nanofluid coolants. In fact, while the reduction of the mechanical effects (erosion, abrasion, corrosion) with regard to millimeter- or micron-sized particles is perhaps undeniable, their negligibility is not proved or sometimes negated due to the smaller momentum imparted by the particles to the walls.
The present study is supported by the EU FP7 Programme NanoHex Project, dedicated to studies for the enhancement of the performance of heat transfer systems using nanofluids.
The test rig has been built at the Laboratory of Thermal-Fluid Dynamics of the Technical Unit for Advanced Technologies for Energy and Industry of ENEA.
Erosion has been tested by making nanofluids circulate for several days and impact on three types of targets made of commercial metals:

- Aluminium
- Copper
- Stainless steel

Also, two targets from Siemens have been tested, obtained from the same aluminium anisotropic alloy used in Power Electronics cold plate - cut along two different axes.
The nanofluids are:

- TiO_2-9%wt supplied by ItN Nanovation AG (a German company specialized in nanoparticles and nanofluids production)
- Al_2O_3-9%wt supplied by ItN
- ZrO_2-9%wt supplied by ItN
- Base fluid of ZrO_2-9%wt supplied by ItN
- SiC-3%wt supplied by the ENEA Technical Unit for Development of Applications of Radiations

All the above nanofluids are obtained from distilled water added with an additive, usually a surfactant, necessary to keep the nanoparticles separate limiting their agglomeration. It acts like a coating around the particles.
Data on the abrasion of plastic materials are also obtained, analyzing the status of the gear pump. The particle agglomeration during the operating life is evaluated by the analysis of small samples of nanofluid extracted at regular intervals.

The HETNA test rig

The HETNA experimental facility (*Hydraulic Experiments on Thermo-mechanical of NAnofluids*) has been designed to obtain experimental comparison of the difference in the behaviour of nanofluid and base fluid without nanoparticles, using two parallel identical loops. Indeed, in some case these differences could be very small, and a very accurate system is required to evaluate them. For sure this is expected to happen where we have to evaluate the increase in mechanical effects (erosion, corrosion etc.) with relatively short-term experiments (days or weeks) and extrapolate the results to the expected operating life of the systems (up to tens of years).
Experimental data on heat transfer available from literature are obtained in a loop filled with the nanofluid, comparing them with the equivalent data obtained at different times filling it with the base fluid. In the case of the erosion tests this may increase the uncertainty of the comparison because it is very difficult to reach identical conditions. This seems to be unacceptable in the case of erosion tests, where smaller differences should be important when extrapolated to long lifetimes.
For this reason the HETNA experimental facility has been designed as two identical loops running simultaneously under the same conditions, one filled with the nanofluid and the other with the base fluid. An additional special feature of the dual loop is the possibility to monitor in real time the difference in the heat transfer rate (not reported in the present work), thus allowing also to adjust the experimental test matrix during the test, on the basis of the results of previous tests. The precision will be higher, because the control system maintains the two loops under identical conditions, and so little variations during the long-term tests will be negligible for the comparison.

Description of the experimental loop

The diagram of each of the two loops is shown in Fig. 1. The flow is maintained by a volumetric gear pump (flow-rate from 2.4 to 230 l/h), measured with a Coriolis flow-meter and remotely controlled by a Labview program. As an alternative to the erosion test section, a second line with a heated pipe can be used for heat transfer tests.

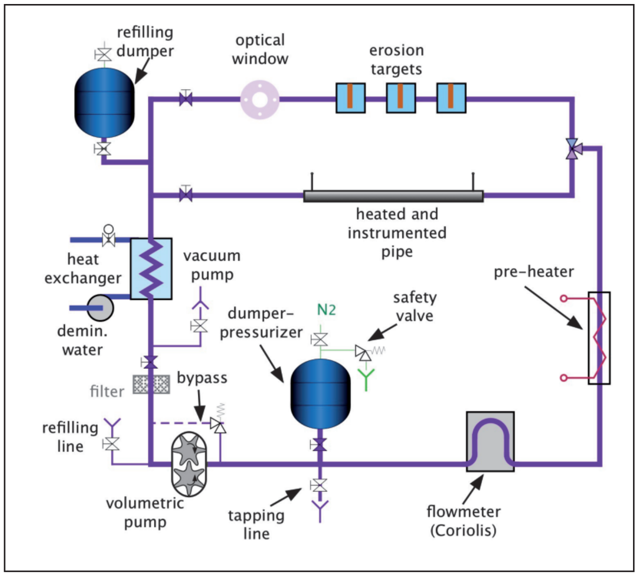

FIGURE 1 Scheme diagram of the loop
Source: ENEA

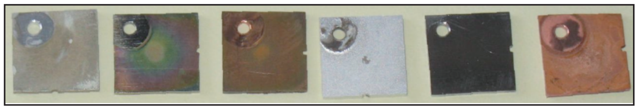

FIGURE 2 Targets after the test: first three on the left in water, last three on the right in ZrO_2
Source: ENEA

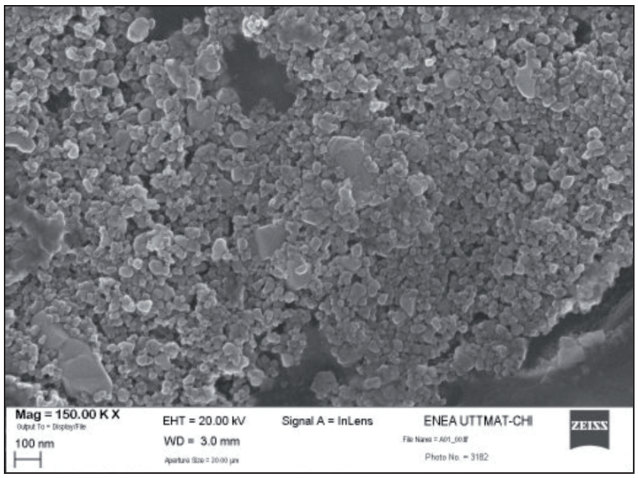

FIGURE 3 TiO_2 nanoparticles (size 20-30 nm)
Source: ENEA

The erosion tests are made letting a fluid jet collide with a target for a given time, usually two weeks, and comparing the surface with the corresponding one located in the base fluid loop by means of a scanning electron microscope (SEM). The measure of the erosion is obtained with an optical profilometer (vertical resolution 0.1 nm, without contact), by scanning the surface and comparing the exposed region with a little masked zone of the target.
The HETNA facility can accommodate up to three targets in each loop (in series) to increase the data production by making more tests at the same time with different targets or different impact velocities (the flowrate is the same, but the velocity depends on the diameter of the nozzle generating the jet. Fig. 2 shows the targets used in a test with the zirconia. In Fig. 3 a deposit of titania particles on the aluminium target is shown.
The eroded mass added to the mixture is negligible, usually of the order of a few ppm of the liquid in the loop, as the test duration is not so long and during this time only a small amount of mass is eroded from the targets.
Agglomeration, settling and sedimentation are evaluated by extracting small samples of nanofluid at regular intervals during the test and measuring the particle size with the laser scattering technique.
Both the measure of the consumption of the pump gears after the test, and the pump performance decrease give an evaluation of the abrasive effect of the nanofluid.
An important feature of the HETNA rig is the reduced volume of nanofluid inventory, less than 1.2 liters.

Experimental results

The results show a different behaviour of the nanofluids examined, and the mechanical effects strongly depend on the target material, as reported in Table 1, where the number in brackets is the ratio between nanofluid erosion and water erosion. In the case of nanofluids, with respect to water, the erosion effect can be remarkable in the worst cases, thus making necessary to consider this problem in the applications where those combinations nanofluid-material are to be used.
Results using TiO_2, still compared with the effect of the water under the same conditions, reveal no dangerous increase in erosion as detected in the experiment.

The Al_2O_3 gave no effect for stainless steel and a significant (but not too large) increase in the erosion on copper. Conversely, with commercial aluminum the erosion has been very large, a hundred times the effect of water. The surface of the two aluminum targets is shown in Fig. 4.

The ZrO_2 gave a similar, if not larger, result for Al_2O_3, with no effect for stainless steel, large effect on copper and very large effect on aluminum. Considering that the nanofluid contains also the surfactant, a test has been performed to evaluate whether this large erosion may be also attributable to the presence of this component. However, the null effect of the base fluid of the ZrO_2 on all the metals testifies that the cause of the increased erosion is due to particles. This is confirmed by the SEM analysis that shows a large mechanical erosion, as shown in Fig. 5.

The last nanofluid tested, the SiC at a lower concentration (3% in weight against 9% of the others) has shown very little effect, not well evaluable because while the profilometer does not measure differences in the surface, the SEM shows that some corrosion has happened, though incrustations of oxides and nanoparticles compensate this lowering of the surface.

Nanofluids have a different behaviour also regarding the abrasion. As said above, it is evaluated by two data obtained from the gears of the pump (made of PTFE+Carbon fiber):

- the weight of the mass lost by the gears during the test;

Nanofluid	Aluminium	Copper	Stainless steel
TiO_2_9wt%	very small increase (1.3)	no effect	no effect
Al_2O_3_9wt%	very large increase (117)	significant increase (4.7)	no effect
ZrO_2_9wt%	very large increase (636)	large increase (15)	no effect
Base fluid of ZrO_2_9wt%	no effect	no effect	no effect
SiC_3wt%	small or no effect	small or no effect	no effect

TABLE 1 Summary of erosion test
Source: ENEA

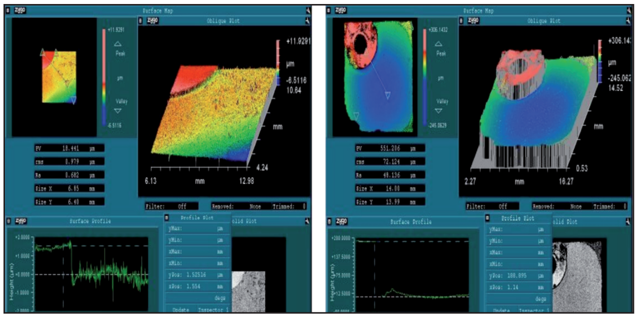

FIGURE 4 Aluminum targets in water (left) and Al_2O_3 (right): surface from the profilometer analysis
Source: ENEA

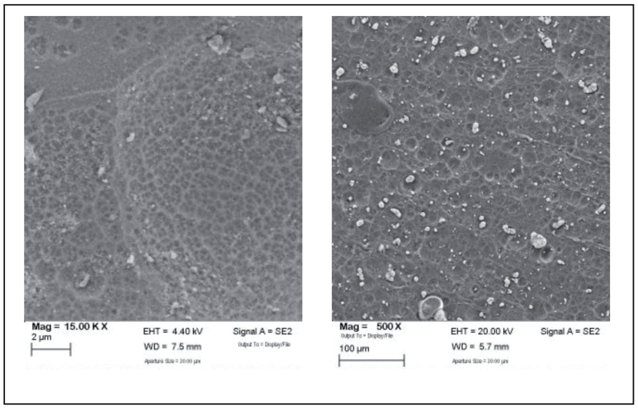

FIGURE 5 Aluminum target in nanofluid ZrO_2 (left) and Al_2O_3 (right), from SEM
Source: ENEA

- the performance deterioration, from the increase of the speed of the nanofluid pump needed to maintain the same water flow-rate.

The results are shown in Fig. 6, where the left axis is the ratio between the rotation velocities of the two pumps, and is referred to the curves, while the right axis is the weight lost and is referred to the square points. Alumina has proved to give the largest damage to the gears, followed by the silica carbide, the zirconia and, last, the titania. No effect has been produced by the base-fluid.

Conclusions

An experimental research is presented, devoted to ascertain the effects of a nanofluid flow impacting metallic surfaces. Data obtained is the difference in the be-

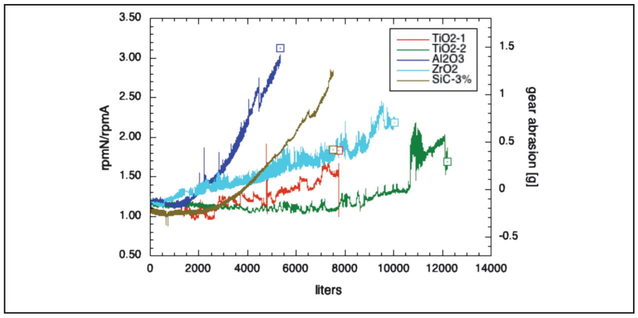

FIGURE 6 Abrasion effect on the pump gears
Source: ENEA

haviour of the different nanofluids when compared with water under the same conditions, i.e., the same impact velocity. Results show that the effect strongly depends on the target material and on the particle material, and in some case is very large and must be properly taken into account as it can shorten the life of components should water be replaced with the nanofluid. The abrasive effect also can be considerable.

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