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Influence of the composition and viscosity of volcanic ashes on their adhesion within gas turbine aeroengines

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ABSTRACT

This paper presents experimental investigations into adhesion characteristics of four types of (Icelandic) volcanic ash (VA). Firstly, powder (~5–50 μm) was injected into a modified vacuum plasma spray set-up and the fractional mass of particles that adhered to a substrate was measured. Secondly, large (~6 mm), dense pellets of each ash were heated and projected at a substrate, with their impact response monitored via high speed photography. The four ashes fall into two groups of two, one with high Si content (>20%) and the other containing less Si, but higher levels of lower valence cations (such as Ca, Mg & Fe). The glass transition temperatures were all relatively low (~650–750 °C), favouring particle adhesion on surfaces in gas turbines. All of the ashes tended to adhere, especially with higher gas temperatures and impingement velocities. However, this tendency was much greater for the two ashes with high levels of the lower valence cations. The high speed photography confirmed that this was due to these two ashes having much lower viscosities (at high strain rates). This behaviour could not have been predicted solely on the basis of T_g or glass content values. However, these cations act as "network-modifiers" in silica-based glasses, effecting sharp reductions in melt viscosity, so inferences about the danger of specific VA may be possible from simple compositional analysis. In any event, it's clearly important for VA being generated during any particular eruption to be sampled (presumably by drones) and analysed, rather than relying solely on remote measurement of atmospheric ash levels.

1. Introduction

Gas turbine aeroengines can be seriously and rapidly damaged by ingested ceramic particles, especially ones that are likely to melt, or at least soften, in flight, and then adhere to solid surfaces on impact. Much ingested particulate has a relatively high softening temperature (>~1300 °C), but this is not the case [1–4] for most types of volcanic ash (VA), which is therefore perceived as particularly dangerous. It's certainly true that a high fraction of ingested particles adhering inside the turbine will lead to serious problems. Even at the VA particle concentration currently classed as "safe" by the CAA (2 mg m^{-3}), a large turbofan engine at full power will ingest more than 1 g s^{-1}. One gram of adhered particulate, corresponding to ~100 million particles of radius 10 μm, could quickly cause extensive physical damage (blockage of cooling channels etc), and even much lower levels than this are likely to cause problems such as premature spallation of thermal barrier coatings [5–8].

Of course, there have been increasing levels of concern over the past 20 years about this hazard [9–12], with much attention being devoted to advanced techniques for monitoring concentrations of VA in the atmosphere [13–16]. However, it's clear that not all suspended particulate, and not all types of VA, are equally hazardous. The particle size is one issue, with particles in the range of ~5–50 μm being of most concern - since they are both large enough to give a Stokes number [2,17–19] that ensures frequent impact with solid surfaces and small enough to become substantially heated during passage through the combustion chamber [4]. Unfortunately, particles in this size range are likely both to remain suspended in the air for long periods (partly due to the relatively low density of most volcanic ashes) and also to enter the combustion chamber of an aeroengine [20,21] (rather than being centrifuged into the by-pass air). Furthermore, VAs can vary substantially in composition (depending primarily on the geology of

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the source area [22,23]) and hence some are likely to be more hazardous than others in terms of their softening temperature and also their viscosity [3,24–29] in the temperature and strain rate ranges of interest, although there is at present very little specific information available in the open literature about this type of property.

The current work involves injection of four different VA powders, comprising particles in this size range of interest, into a set-up designed to simulate passage through a combustion chamber and subsequent projection towards a solid surface. Deposition rates have been measured over a range of conditions. These studies are complemented by high speed photography of pellets (made by sintering the VA powders) after being heated and projected at a substrate.

2. Experimental procedures

2.1. Powder characterisation

Four ashes have been obtained, from the volcanic eruptions at: (a) Laki (from the fissure eruption of 1783-4 in south-central Iceland), (b) Eldgja (from the fissure eruption of 934, very close to Laki), (c) Hekla 4 - Hekla is a highly active strato-volcano located about 70 km south-west of Laki, which last erupted in 2000 - and (d) Askja 1875 - another active strato-volcano, located about 150 km north-east of Laki, which last erupted in 1961. Papers are available [30–33] covering the details of these eruptions. It's perhaps worth noting at this point that strato-volcanoes, which are characterised by a steep profile, tend to emit highly viscous lava, which cools and hardens before spreading very far [34], although it should be recognised that this is a generalisation and emissions from the same volcano during different eruptions can sometimes vary significantly in composition and viscosity. Such high viscosity also tends to promote high internal pressures, and hence more explosive eruptions [35]. It can thus be seen that an expectation might arise for these four materials to fall into two groups, one comprising ashes (a) and (b) and the other ashes (c) and (d).

The as-received ashes were ground in a ball mill and then passed through a sieve with a mesh spacing of the order of 40 μm. In all cases, this operation produced particle size distributions ranging from about 5 μm to around 50–60 μm. A typical size distribution, referring in that case to the Laki ash, is shown in a previous publication [4]. The chemical compositions of the four ashes, obtained from EDX data, are shown in Fig.1. It can be seen that the concept of there being two groupings is reinforced by this plot, with Laki and Eldgja being similar, as are Hekla and Askja, but with significant differences between the two pairs. The Laki and Eldgja ashes contain only about 15%Si, plus another 20% or so of various other cations, while the Hekla and Askja ashes contain over 20%Si, but less than 15% of the other cations. This is broadly consistent with the concept of material from the Hekla and Askja eruptions being more viscous, since these (low valance) cations are known to act as “network-modifiers” in inorganic glasses, breaking up the linkages between the silica coordination octahedra and hence reducing the viscosity, whereas high silica glasses are expected to be more viscous [36,37]. The higher contents of the divalent (Fe, Ca and Mg) ions in Laki and Eldgja are particularly noticeable.

The phase constitutions of these ashes were investigated using X-ray diffraction. The spectra are shown in Fig.2, together with indications of the phase proportions that they represent. It can be seen that both Hekla and Askja are fully amorphous, while the other two contain significant proportions of two crystalline phases (It was confirmed in a previous publication [4] that most individual particles in the Laki ash are either amorphous or partially crystalline and this is also the case for the Eldgja ash: indexing of the crystalline peaks in Fig.2 is also included in that paper).

A Netzsch dilatometer was used to explore the “softening” behaviour (glass transition temperature and “melting point”) of these ashes. Again, details of the procedure used, which involves the actuation rod applying a small pressure to a powder compact while it is heated, are given in the previous paper [4]. The four plots of displacement against temperature (being increased at 5 °C min^{-1}) are shown in Fig.3. Initially, the powder compact expands on heating, but then a contraction is observed (on passing through the glass transition temperature, T_g), as the amorphous fraction softens, so that powder particles start to deform and the compact becomes denser. For the partially crystalline powders, contraction accelerates when the crystalline phases finally melt at T_m. It can be seen from Fig.3 that all of the T_g values are in the approximate range 650–750 °C, while T_m is ~1000–1100 °C for the Laki and Eldgja.

SEM micrographs of the four powders were obtained by

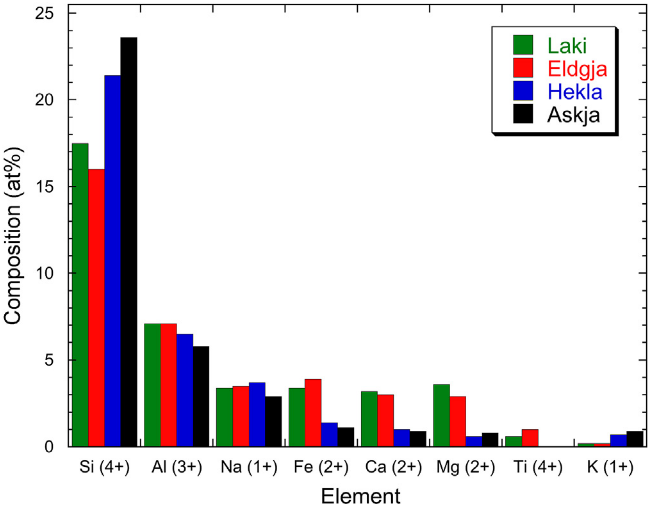

Fig. 1. Compositions of the four ashes, as obtained by EDX (excluding the oxygen content). The expected (predominant) valence states of these cations are indicated.

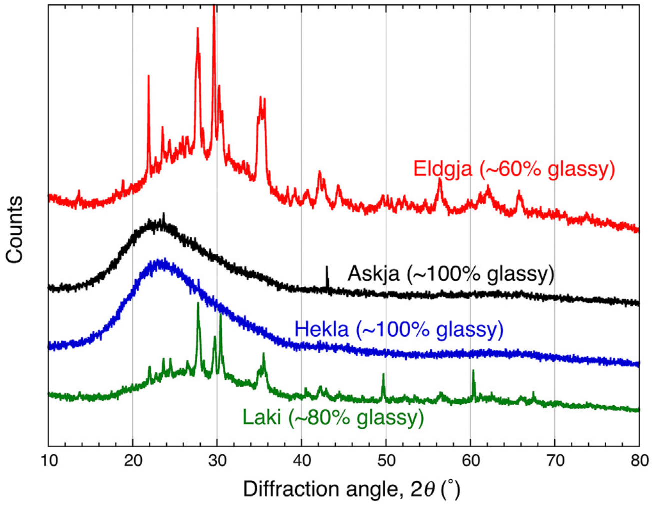

Fig. 2. XRD spectra from the four ashes, with indications of the approximate glass contents (obtained by Rietveldt analysis). The crystalline peaks in the Eldgja and Laki plots are all from two phases, clinopyroxene (~60%) and plagioclase (~40%).